Complementarity of satellite OCR and in situ measurements (with emphasize on profiling floats): towards integrated observation systems for biogeochemistry and ecosystems

Hervé Claustre
Laboratoire d'Océanographie de Villefranche, France

Presentation outline

- Observation: the context and the challenge
  - Undersampled ocean, ocean under stress, various reasons/motivation for observing…
- The various bricks of (in situ) observing systems
  - Gliders, mammals, moorings, ship, floats…
- Developing synergies between OCR satellite and in situ components
  - Transfert function, 3D/4D climatologies, bio-optical anomalies, phytoplankton biomass cycle, cal/val, deployment strategies…

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  - Various science application: 3D/4D climatogies, bio-optical anomalies, phytoplankton biomass cycle, cal/val, deployment strategies…

An undersampled ocean… under stress

- Sampling and data collection are fundamental for improving our knowledge and understanding of the Ocean, but….
- …The Ocean is vast, remote and harsh…
  - 70% of the earth surface
  - Average depth of 3800 m
  - Storms, pressure, darkness
- …and thus mostly unknown

An undersampled ocean

looking backward….(Munk 2000)

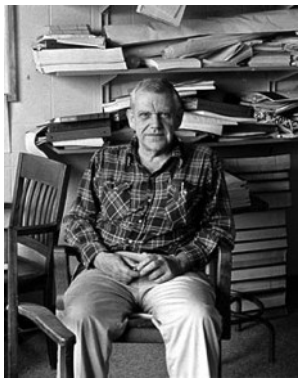
- *"If I were to choose a single phrase to characterize the first century of modern Oceanography it would be a century of undersampling"*
- *"In the early 1970's, we were living under the axiom that what is not done from ships is not oceanography…"*
- And with respect to discovery of mesoscale activity in the late 1960's:
  "For one hundred years this overwhelming mesoscale dynamics had fallen through the loose mesh of traditional sampling…."

Munk, 2000: Oceanography before, and after, the advent of satellite

An undersampled ocean

Stommel (1989) was looking forward… in 2021

- *"Establish the World Ocean Observing System [WOOS], a facility capable of monitoring the global ocean",*
- *"Using a fleet of small neutrally-buoyant floats called Slocums that draw their power from the temperature stratification of the ocean"*
- *"They migrate vertically through the ocean by changing ballast, and they can be steered horizontally by gliding on wings at about 35 degrees angle"..*
- *"Each day we get about 3000 CTD profiles from our Sentinel fleet"…..*

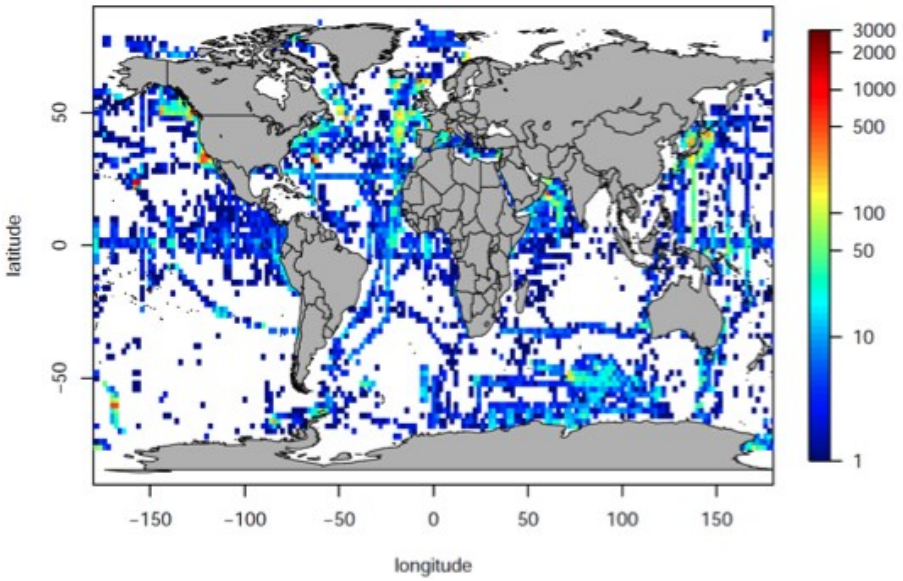


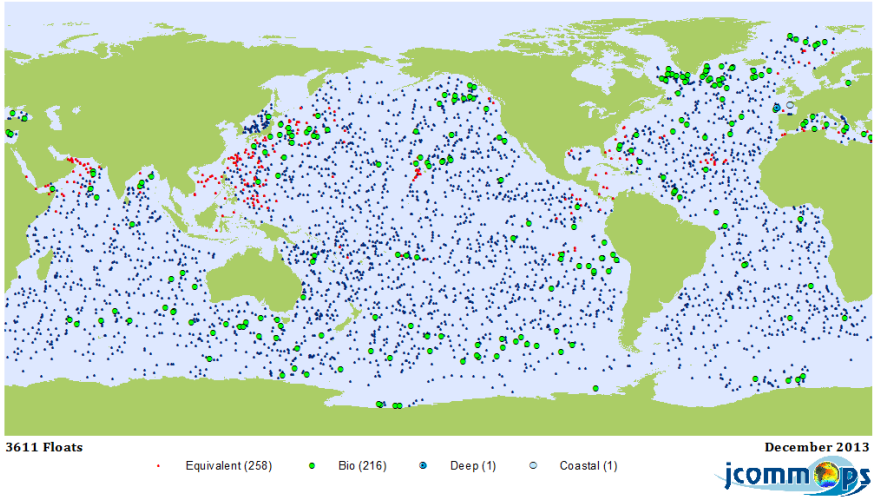
Stommel, 1989: The slocum mission. Oceanography

An undersampled ocean

- Munk and Stommel were physical oceanographers…mostly (only) concerned by physical properties (T and S)!
- Ocean under-sampling is even more critical for biogeochemistry

e.g. undersampled Chla





Pre Bio-Argo era

- ~ 40,000 Chla fluorescence profiles over 1970-2012.
- Un-calibrated profiles.
- Scattered in various databases

Argo era

- More than 1.5 10^6 QC profiles.
- A single accessible database.

An undersampled ocean…. under stress

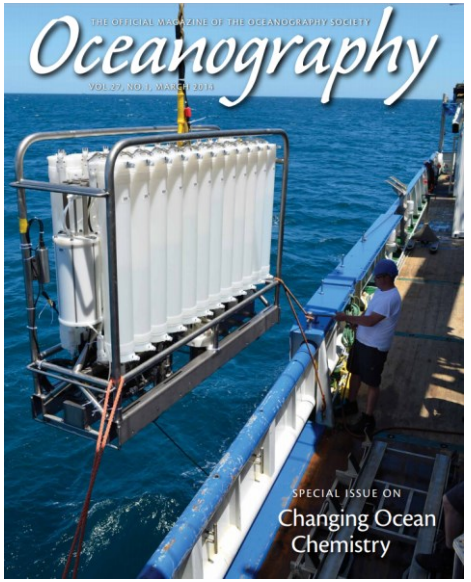
PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

Phil. Trans. R. Soc. A (2011) **369**, 1980–1996
doi:10.1098/rsta.2011.0003

REVIEW

Warming up, turning sour, losing breath: ocean biogeochemistry under global change

BY NICOLAS GRUBER*



- Ocean warming increase stratification
  - Decrease in nutrient fluxes
  - Ocean desoxygenation
- Uptake of anthropogenic CO2 and acidification
- Ice cover reduction

An undersampled ocean….under stress

We need to observe more and better by:

- Increasing the spatial and temporal resolution of the measurements:
  - ❑ Ship + new autonomous platforms
- Increasing the diversity of measurements:
  - ❑ new sensors implemented on platforms

What are our motivation for observing the Ocean?

SCIENCE-DRIVEN QUESTIONS: OCEAN & CLIMATE CHANGE RESEARCH

- improved understanding of change and variability in ocean biology and biogeochemistry (over a large range of spatial and temporal scales)
- reduction of uncertainties in biogeochemical fluxes/ global ocean metabolism (Net Community Production, C export, N supply…)?

What are our motivation for observing the Ocean?

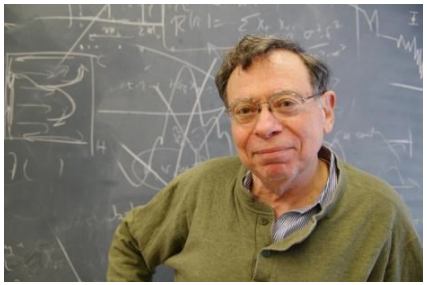
SOCIETAL NEEDS -DRIVEN QUESTIONS

- Monitoring and assessing how the oceans are changing; warning systems (e.g red tides, oil spills) ; good environmental practices; fisheries; biodiversity conservation; **Open data** to scientists, users and decision-makers.

- **Operational oceanography**: model (+ in situ data + satellite data) for sea state, ocean biogeochemistry and ecosystem predictability;

- **Models** need to be initialized, tested and **validated** against observations on all time and space scales.

Wunsh: "*One of the major issues facing oceanography is that high resolution models become fundamentally untestable, so we need more repeated observations at finer space and time scales*".



What are our motivation for observing the Ocean?

EXPLORATION AND POTENTIAL DISCOVERIES

- We all expect that **new oceanographic instruments** working on **previously unmeasured time or spatial scales**, will led to surprising, sometimes startling**, discoveries** that we did not anticipated.

« *Exploration for its own sake has always motivated biological oceanographers, but as the discipline matured, this motivation became less fashionable. NSF has never supported biological oceanographers for the sole purpose of looking for strange organisms,* ***yet discoveries is what make biological oceanography so much fun*** »
Barber (2010) in 50 years of discoveries, National Science Fundation 1950-2000

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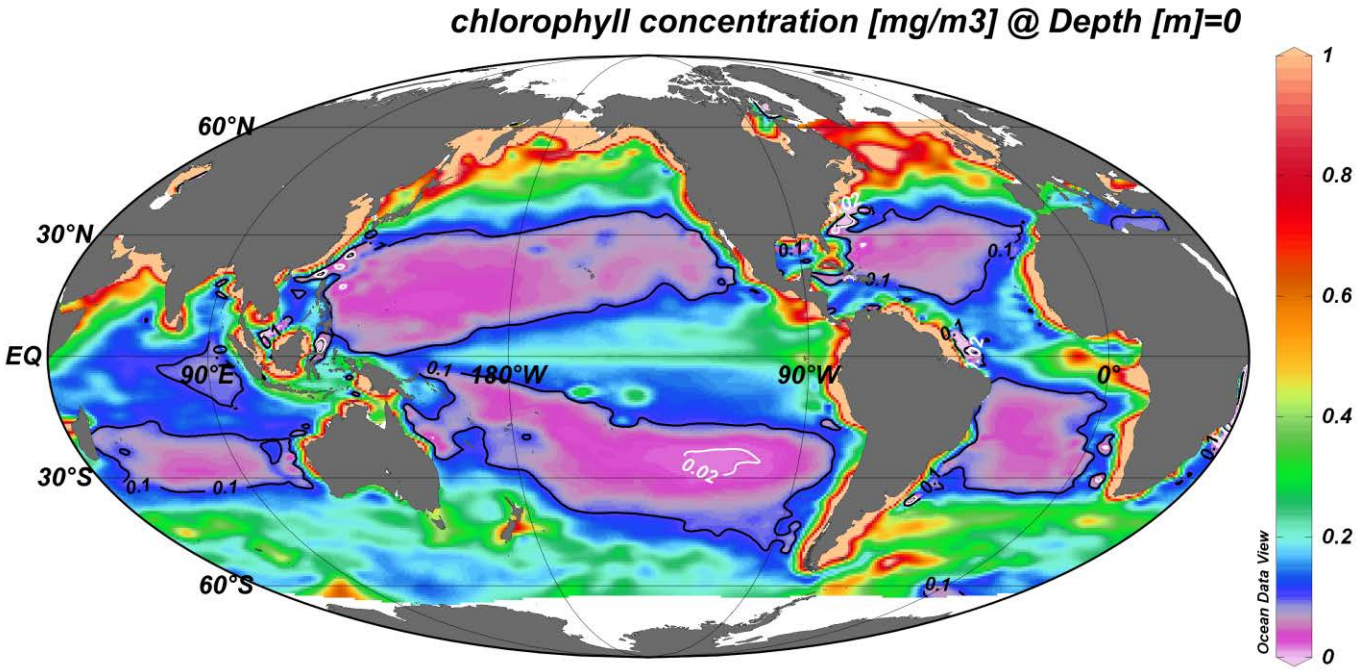
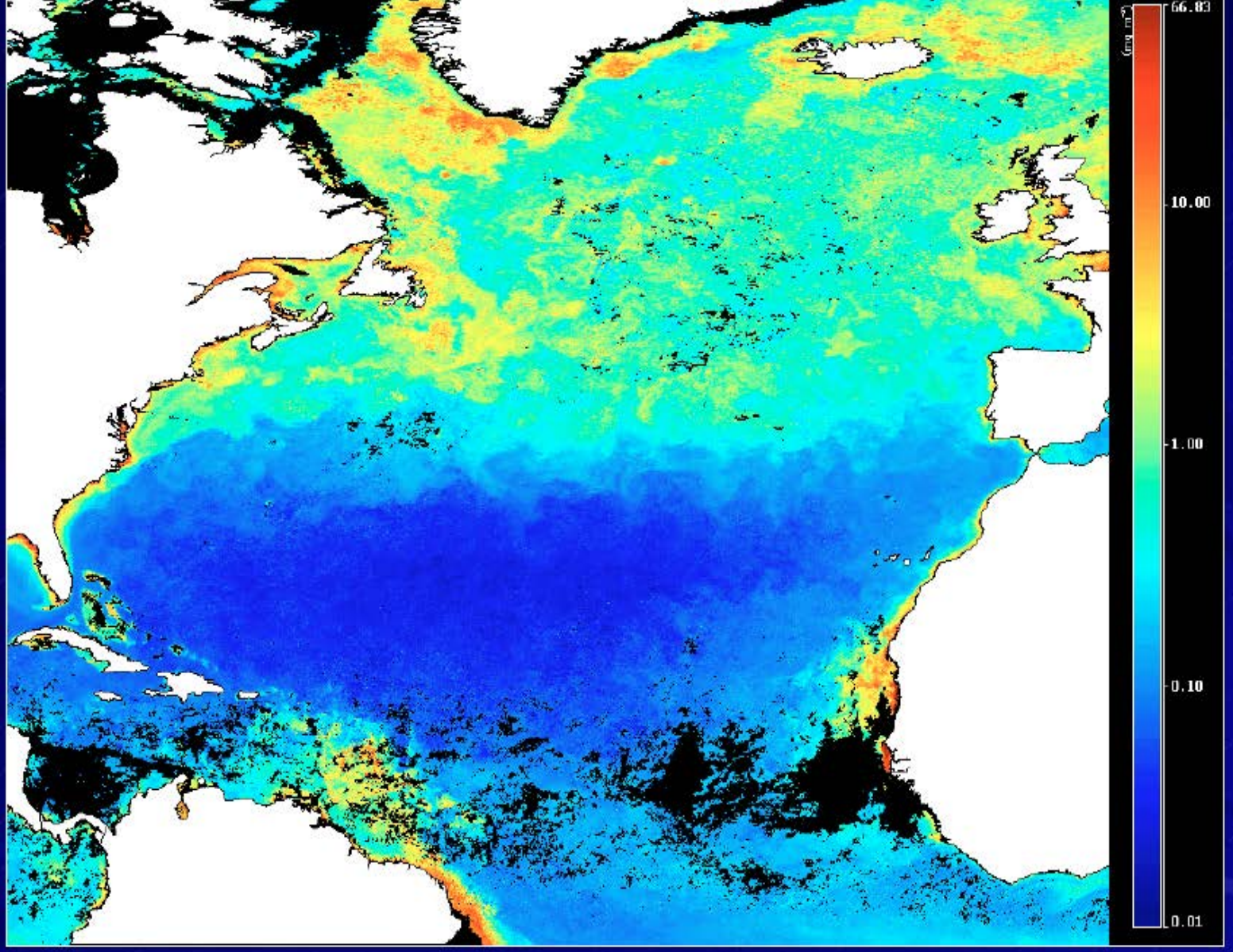
Ocean Color Radiometry

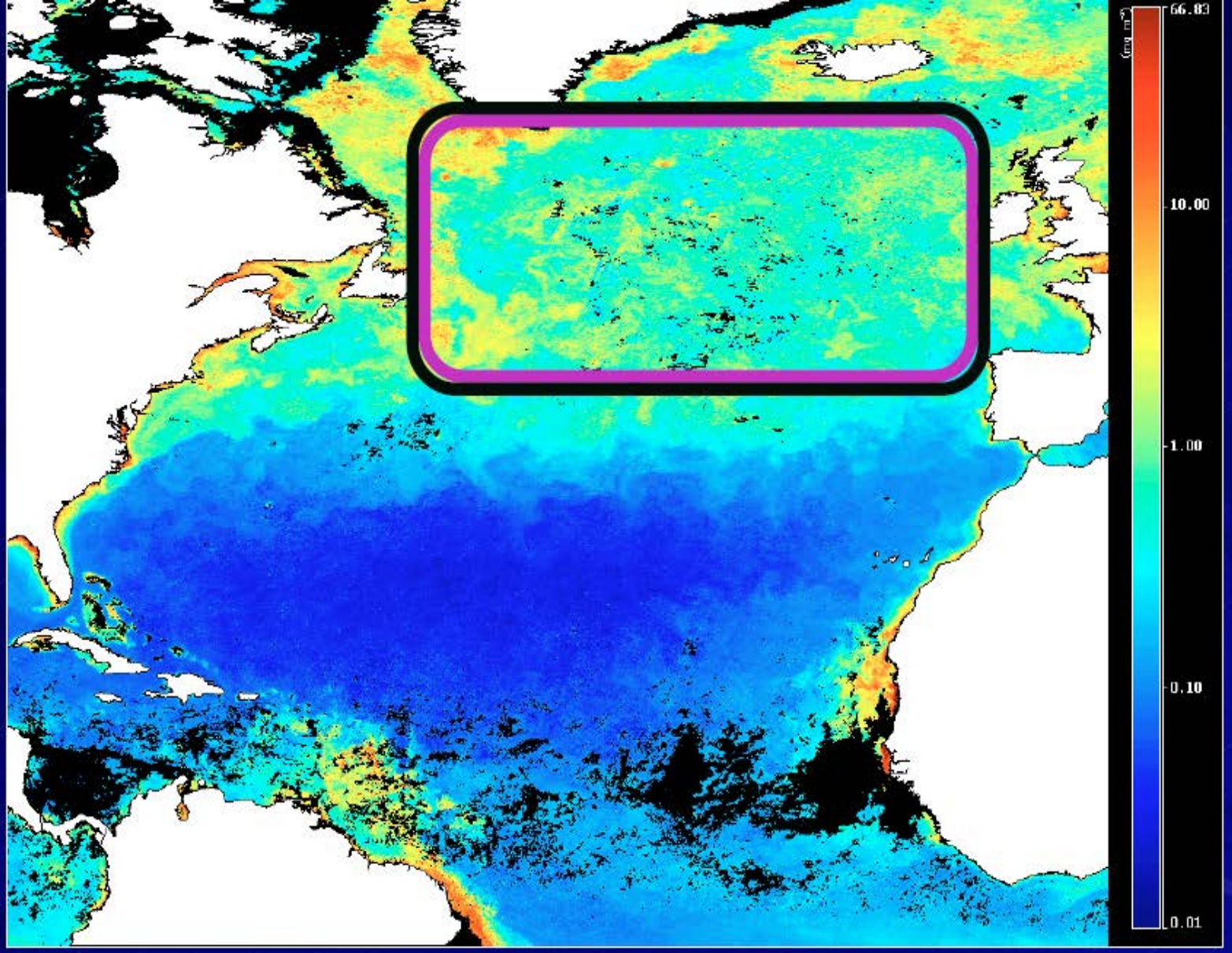


- Diverse products : Chla, bbp (POC), CDM (detrital), phytoplankton functional types, particle size indices, primary production
- global & quasi-synoptic
- « long-term « coherent time series

….but Limited to the upper layer (1/5 of the so –called euphotic zone) & issue when clouds



SeaWiFS chlorophyll, NA spring bloom, May 2003



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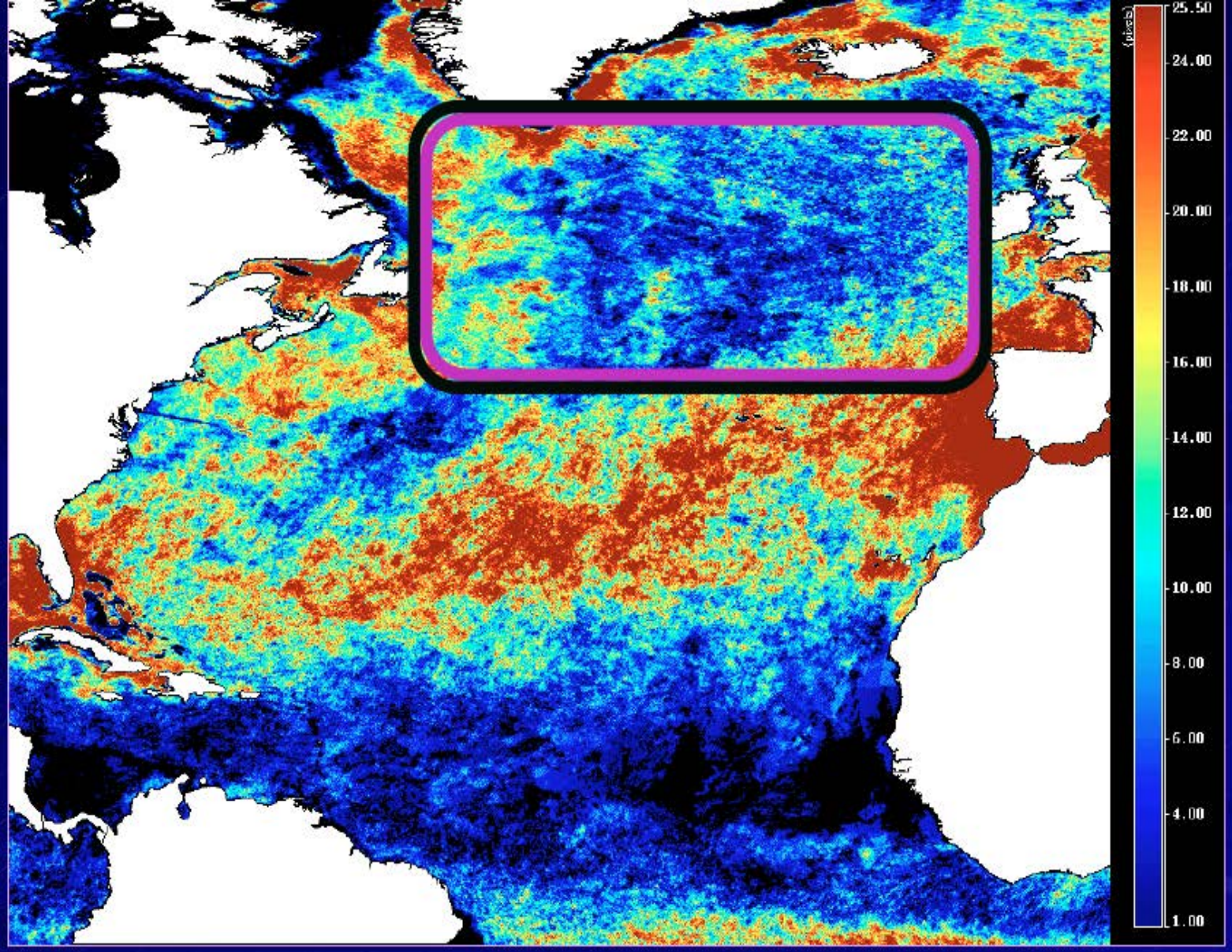
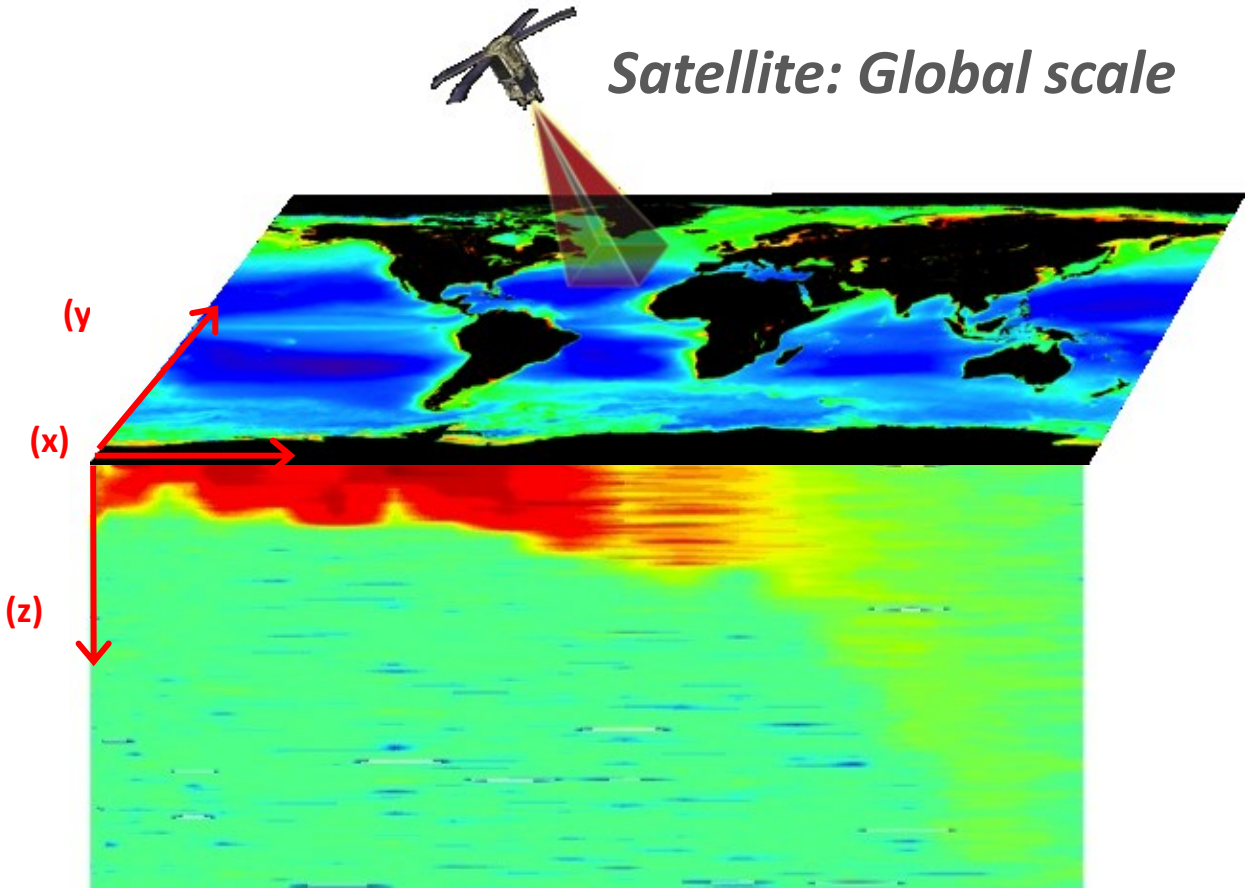


SeaWiFS pixel density, NA spring bloom, May 2003

Expected Benefits of a combined Ocean Color remote sensing - in situ approach

- ✓ In situ brings vertical dimension missed by the satellite and observations under cloud cover or no light conditions
- ✓ Remote sensing might provides the spatio-temporal extrapolation to in situ measurements

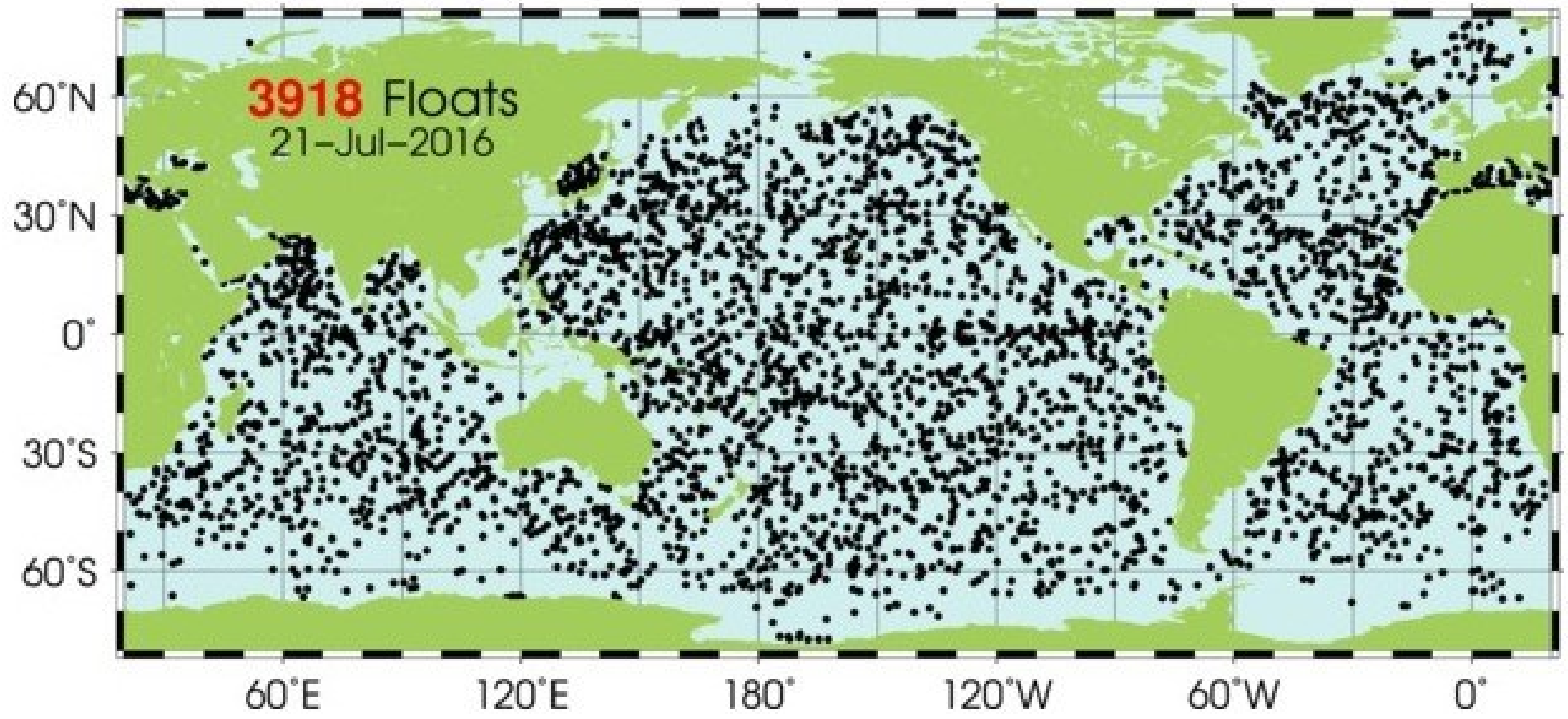


→ 3D/4D OCEAN BIOGEOCHEMISTRY

The various components of the in situ observation system for biogeochemical cycles and ecosystems

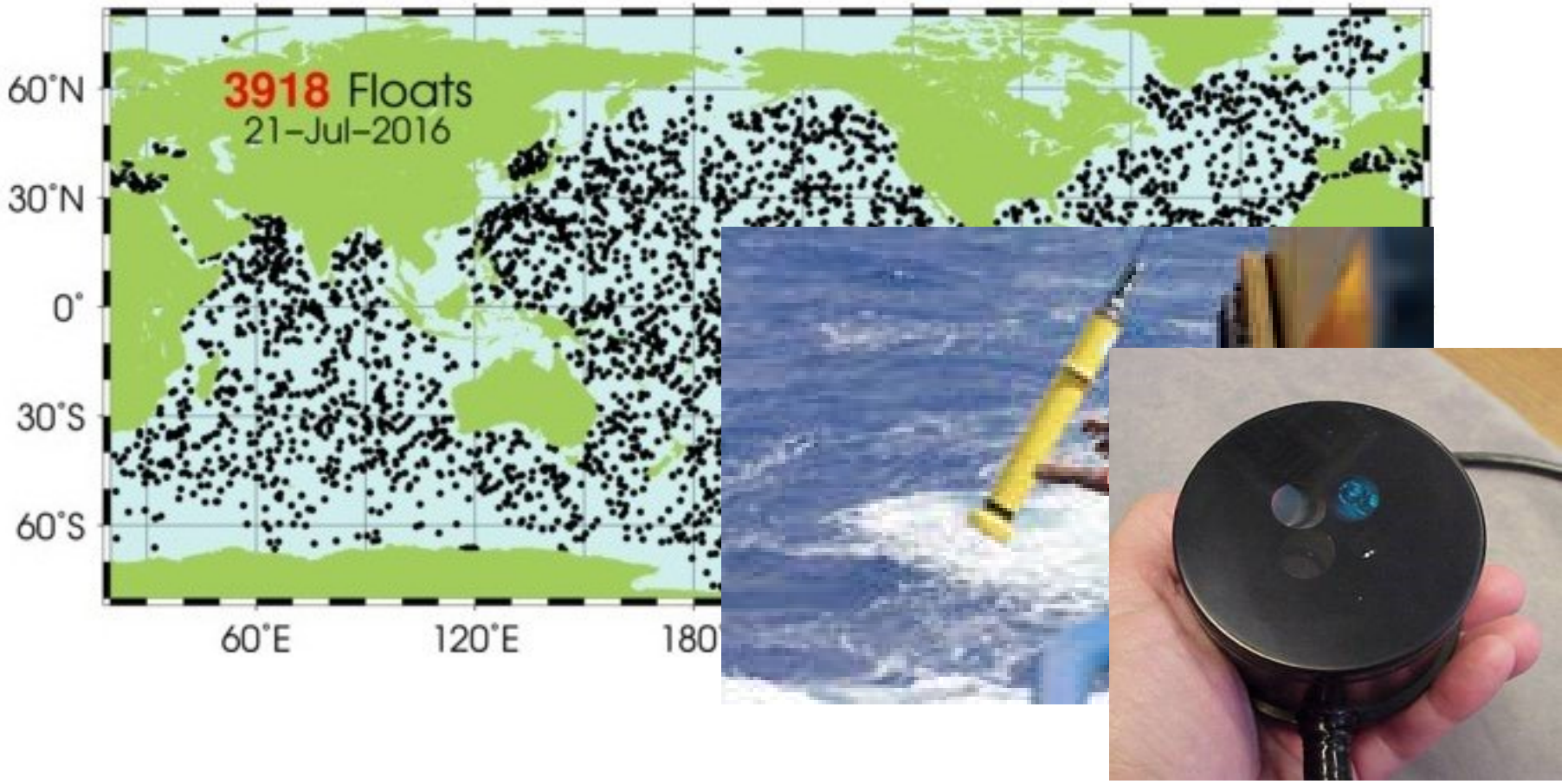
- Floats (Biogeochemical-Argo program)
- Gliders
- Instrumented mammals (MEOP program)
- Mooring (OceanSites)
- Repeated cruise transect (Go-Ship program)

Argo program: the success story



Today, more than 98 % of T&S profiles are acquired by Argo floats.

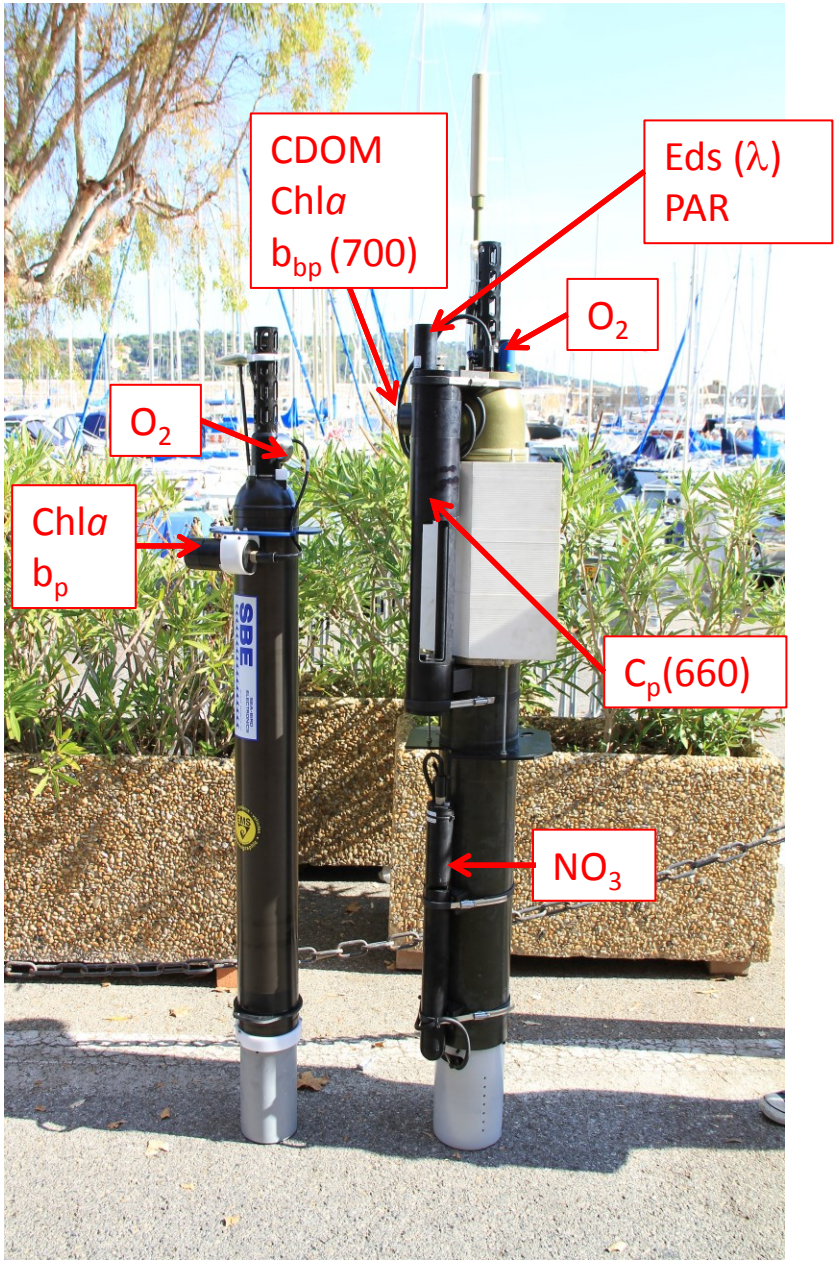
From Argo to Bio-Argo / BGC-Argo



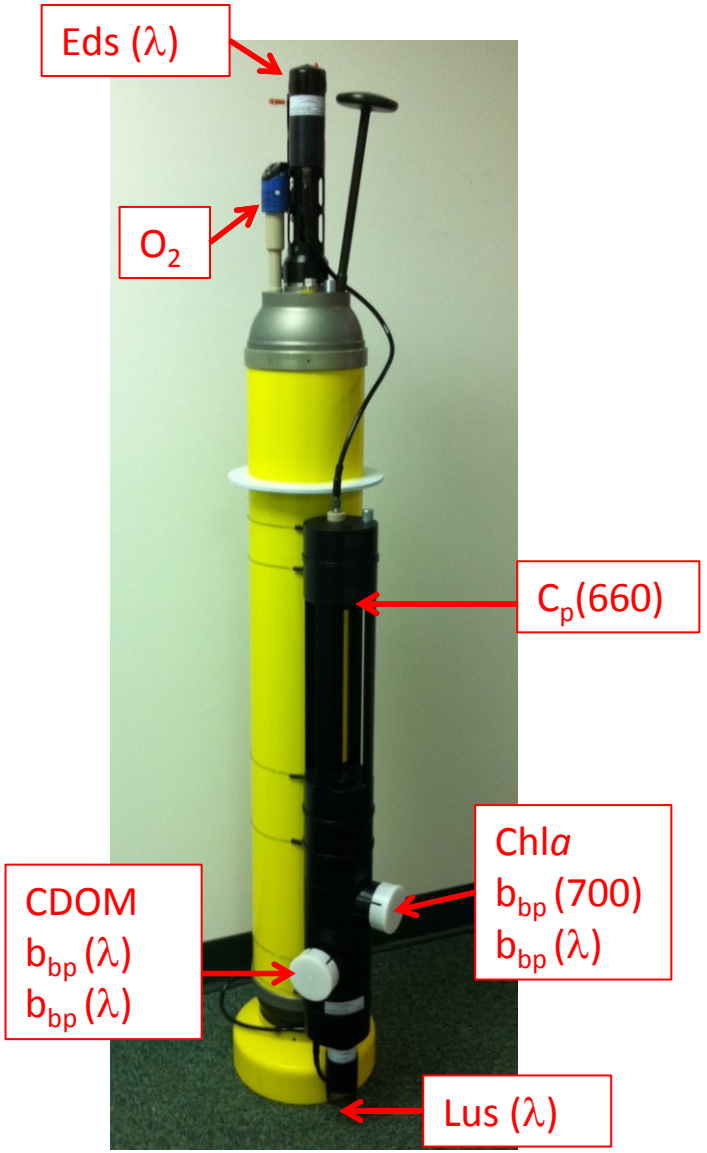
Bio-Argo Floats

- Measurements
  - **PAR, Ed(380), Ed(412), Ed(490)**
  - **b_{bp}(700)**: POC proxy
  - **Chla fluorescence**: Chla concentration proxy
  - **CDOM fluorescence**: detrital component
  - O2
  - NO3
  - pH
  - *pCO2, passive acoustic, video*
- Missions
  - Temporal resolution configurable: from **diel cycle** to Argo 10 day cycling mode: adaptative sampling strategy
  - Vertical configuration configurable: **up to 0.1m** resolution

Biogeochemical floats

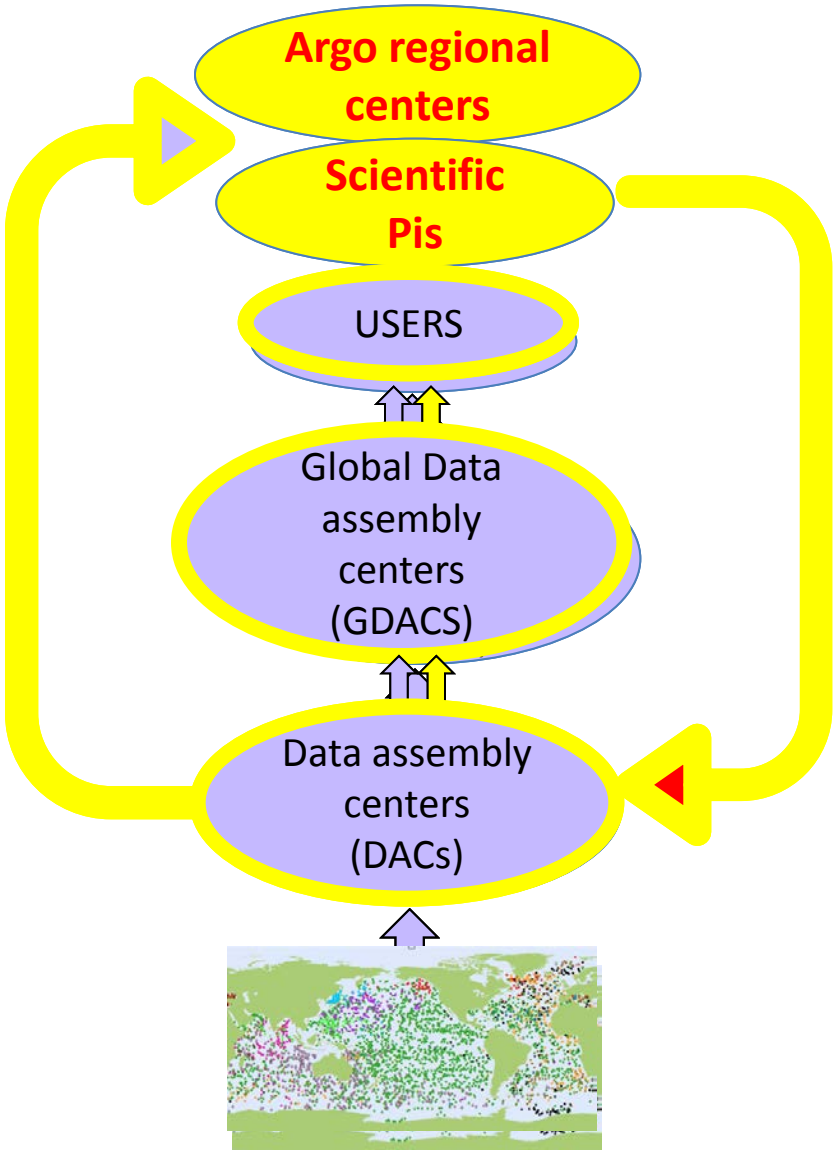


NAVIS PROVOR



APEX

Data management



Real-time QC and distribution

Delayed-mode QC and distribution

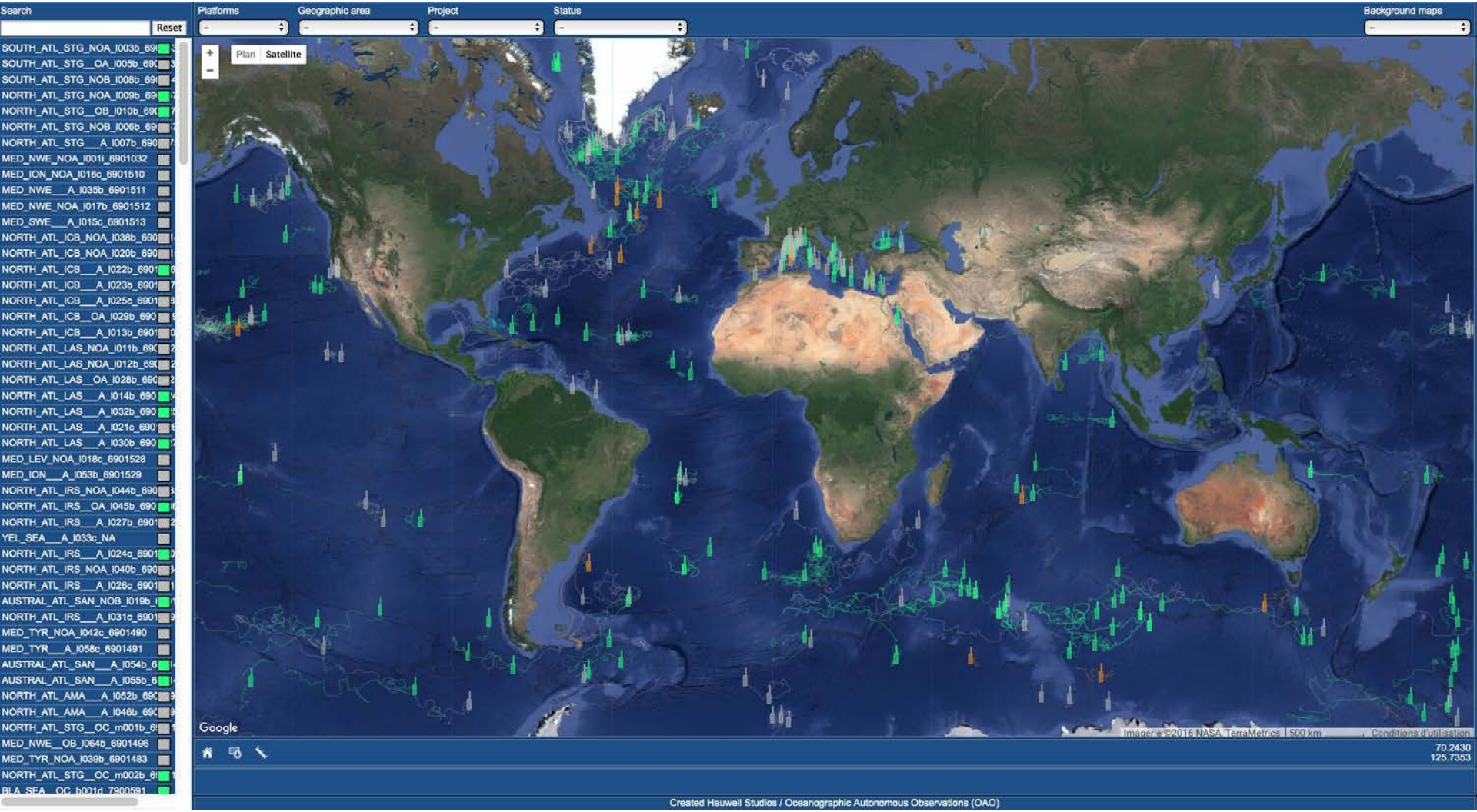
Bio-Argo data stream has to follow the same mode

To start, six variables are considered

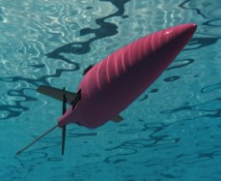
- O2
- NO3
- pH
- Chla
- b_b & turbidity
- radiometry

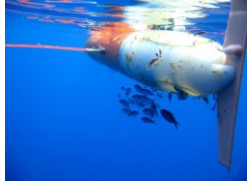
The place to develop the data stream: the **Argo Data Management Team**

Bio-Argo: Data vizualisation



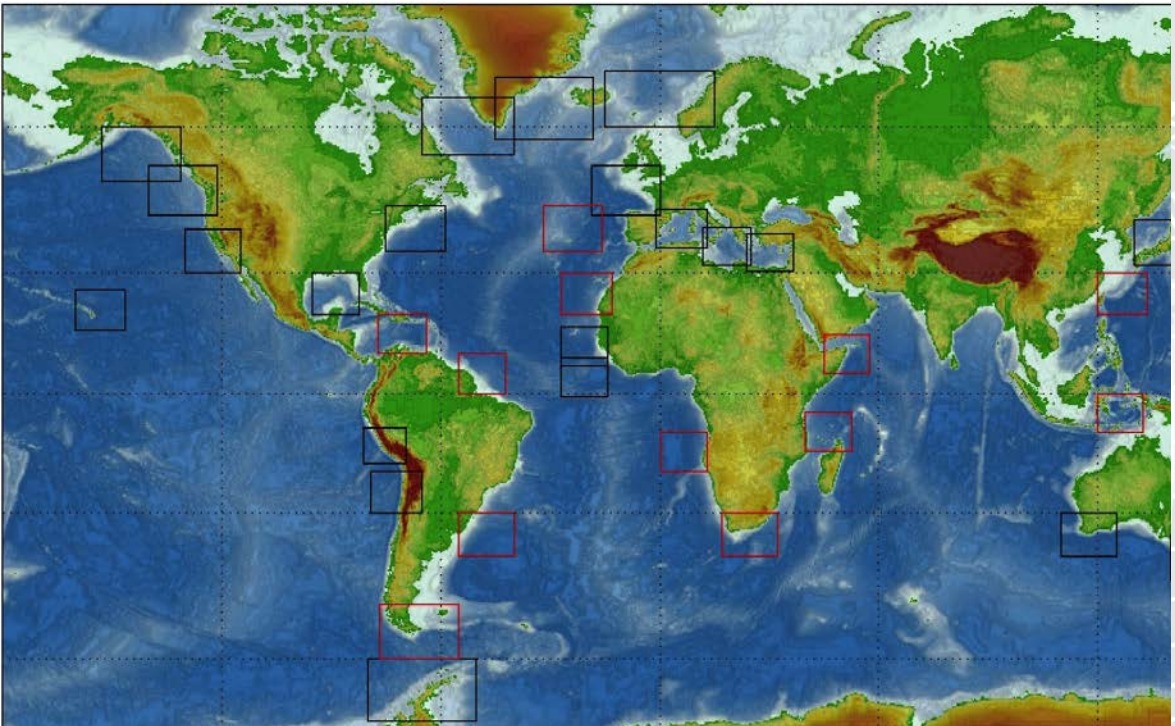
http://www.oao.obs-vlfr.fr/maps/en/





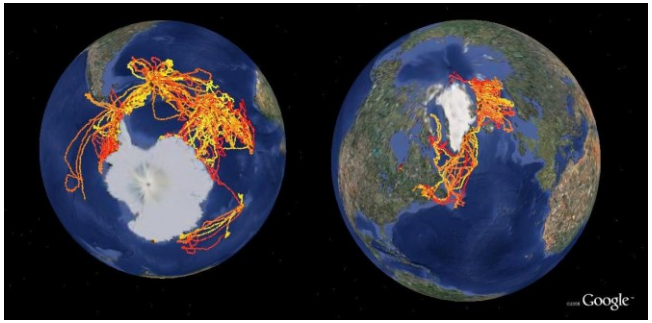
"Biogeochemical" Glider

- Same "biogeochemical" sensors / variables as for floats: Chl*a*, O_2, bb, NO_3, pH?
- Ideal for sub-meso / meso scale (1km-100 km) process studies investigations
- Complementary to floats for enhancing spatial / temporal coverage in critical areas for biogeochemistry and ecosystems:
  - open ocean / coastal interface.
  - Regional seas.
  - Eastern boundary currents.

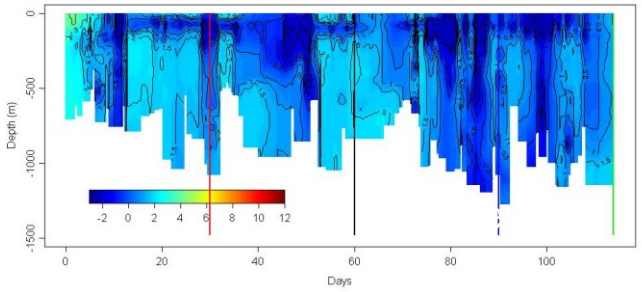


Instrumented mammals at high latitudes

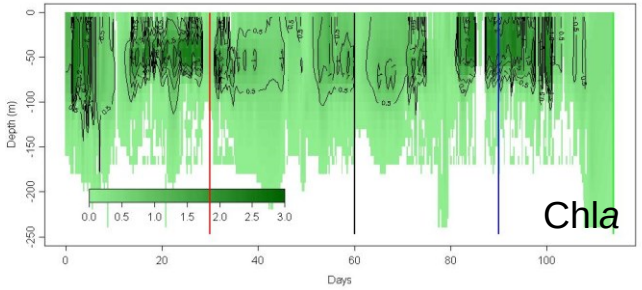
- Animal-borne systems nicely complement gliders and floats at polar latitudes.



- Implementing bio-sensors on animals even more complicated than on floats and gliders
  - Argos telemetry, data reduction, size and energy

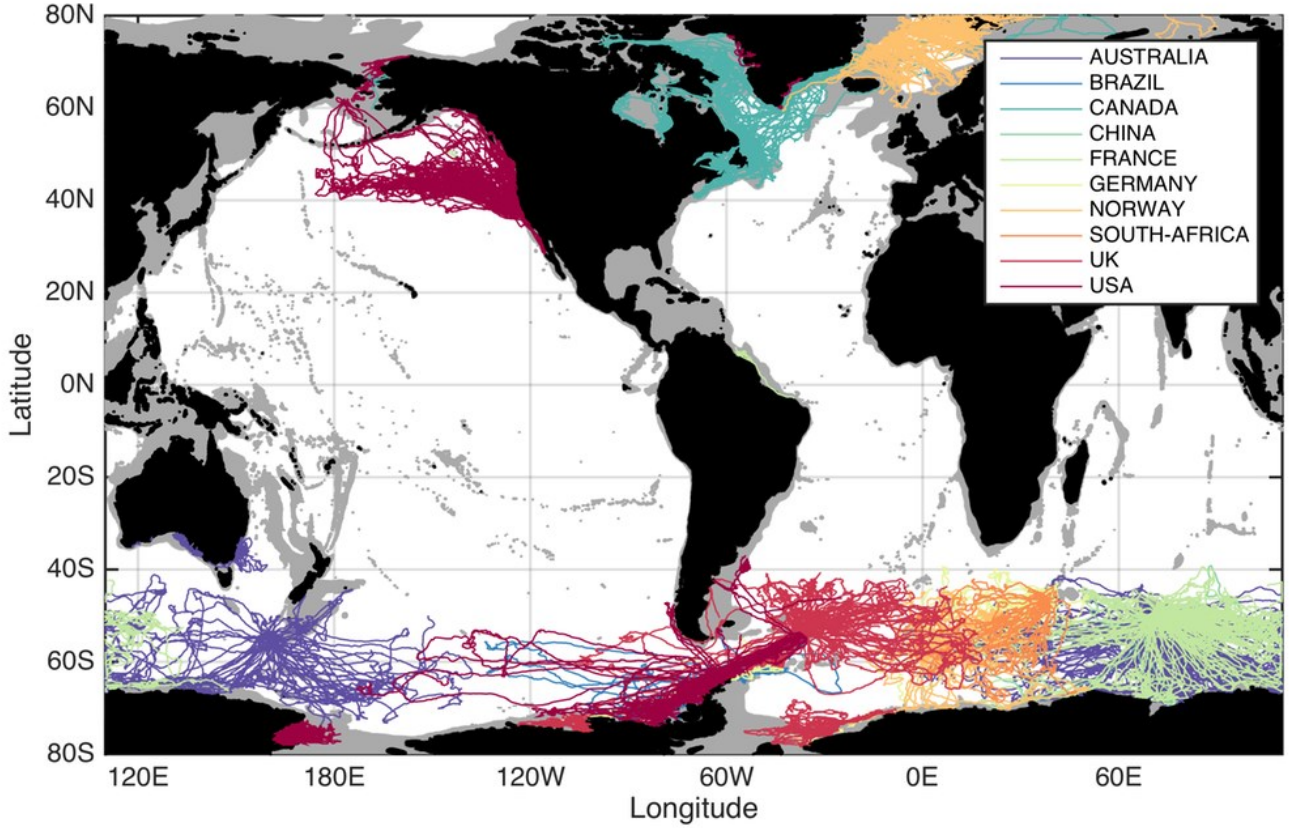


- Promising Chl*a* measurements



- O_2 on the way.

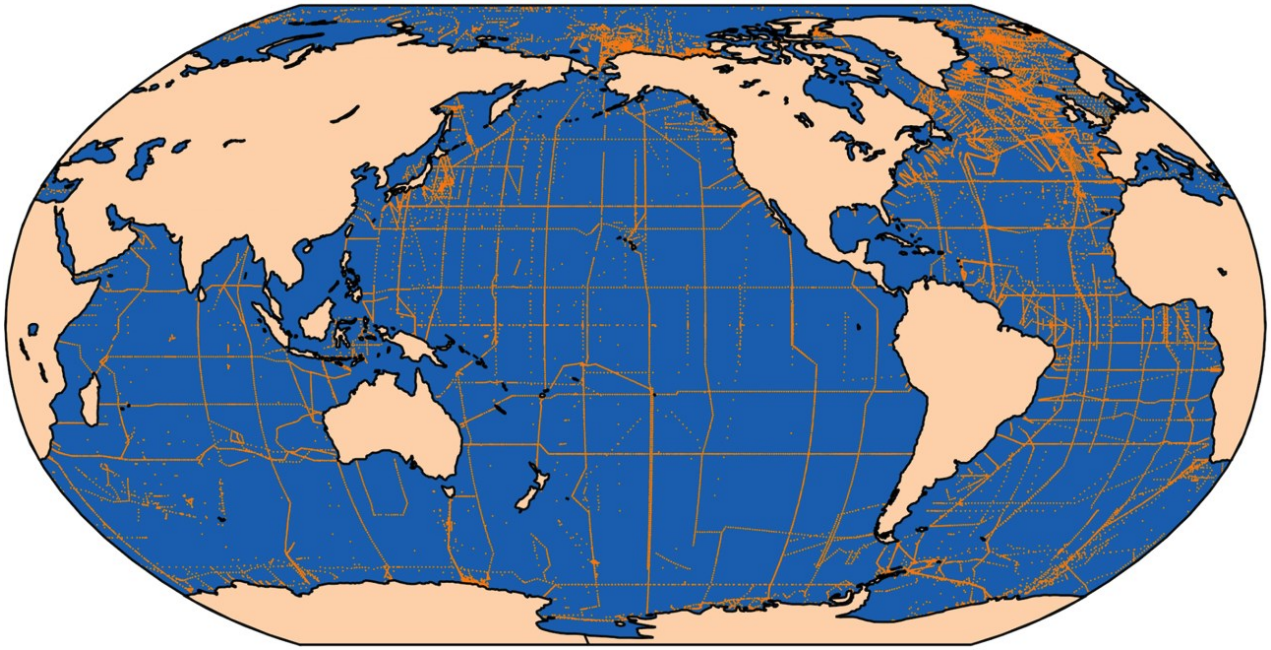
MEOP-CTD dataset : 517429 profiles, 171 deployments, 1197 tags



Ship-based Repeat Hydrography & Biogeochemical measurements

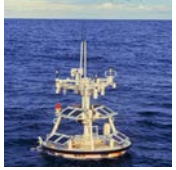
- Already: the variable of CO2 system and dissolved oxygen are “core variables”.
- Concept of Level 1 (mandatory), Level 2 (recommended) and Level 3 variables (interesting but optional: most of bio-optical variables of interest)

The GLODAP V2 data base

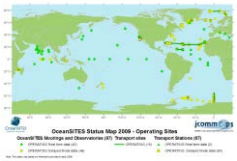


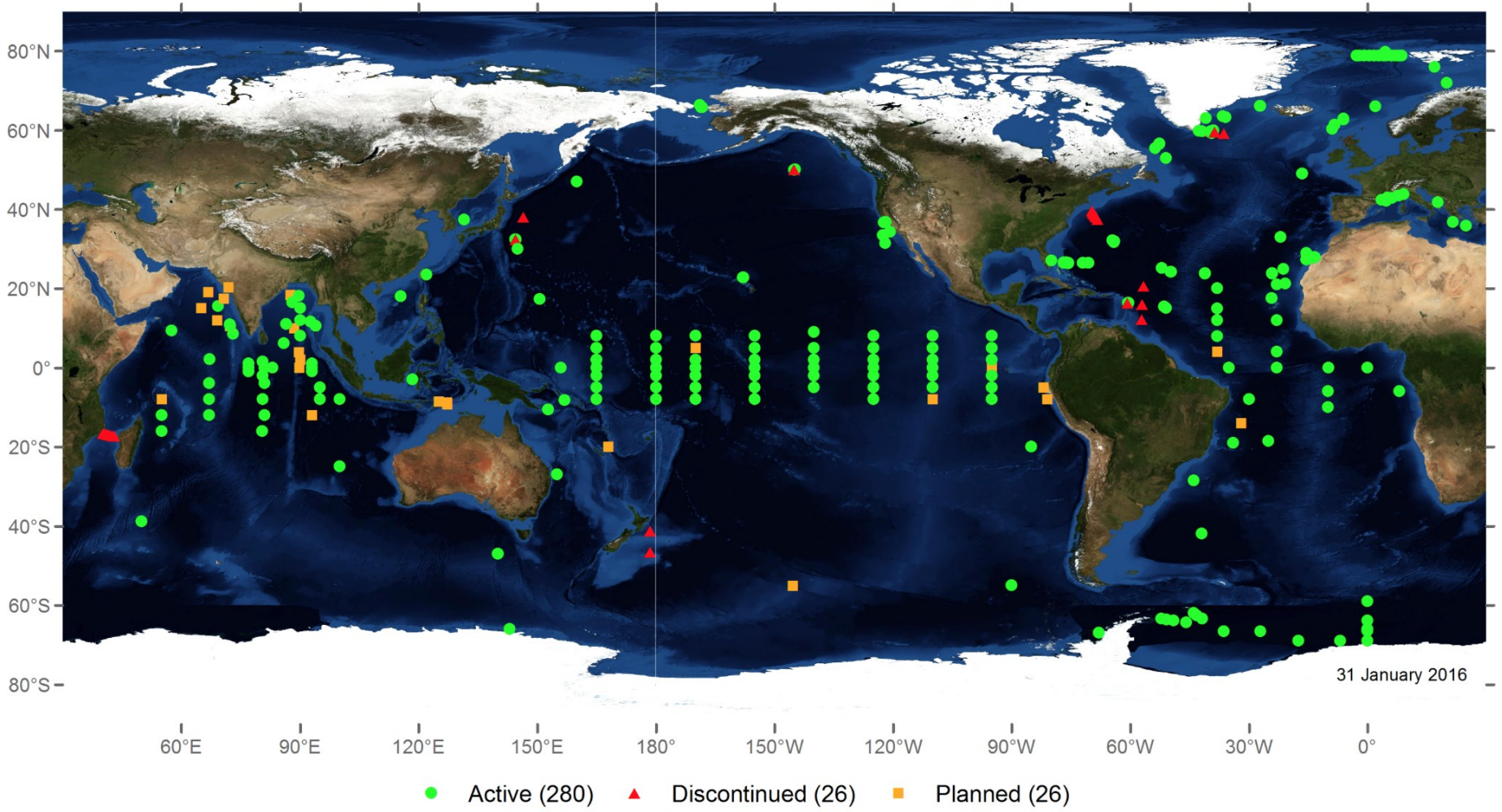
- Decadal survey requiring full basin synopticity (over <3 years)
- Sub-set of decadal survey line every 2-3 years
- Ideal cruises for deployment of biogeochemical floats (simultaneous reference discrete measurements requited for QC).

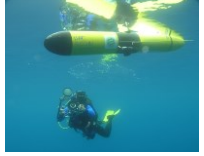
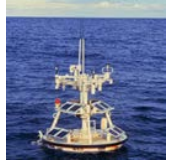
OceanSITES
Taking the pulse of the global ocean



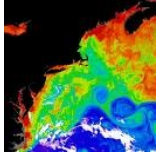
Eulerian Time series and Biogeochemical measurements



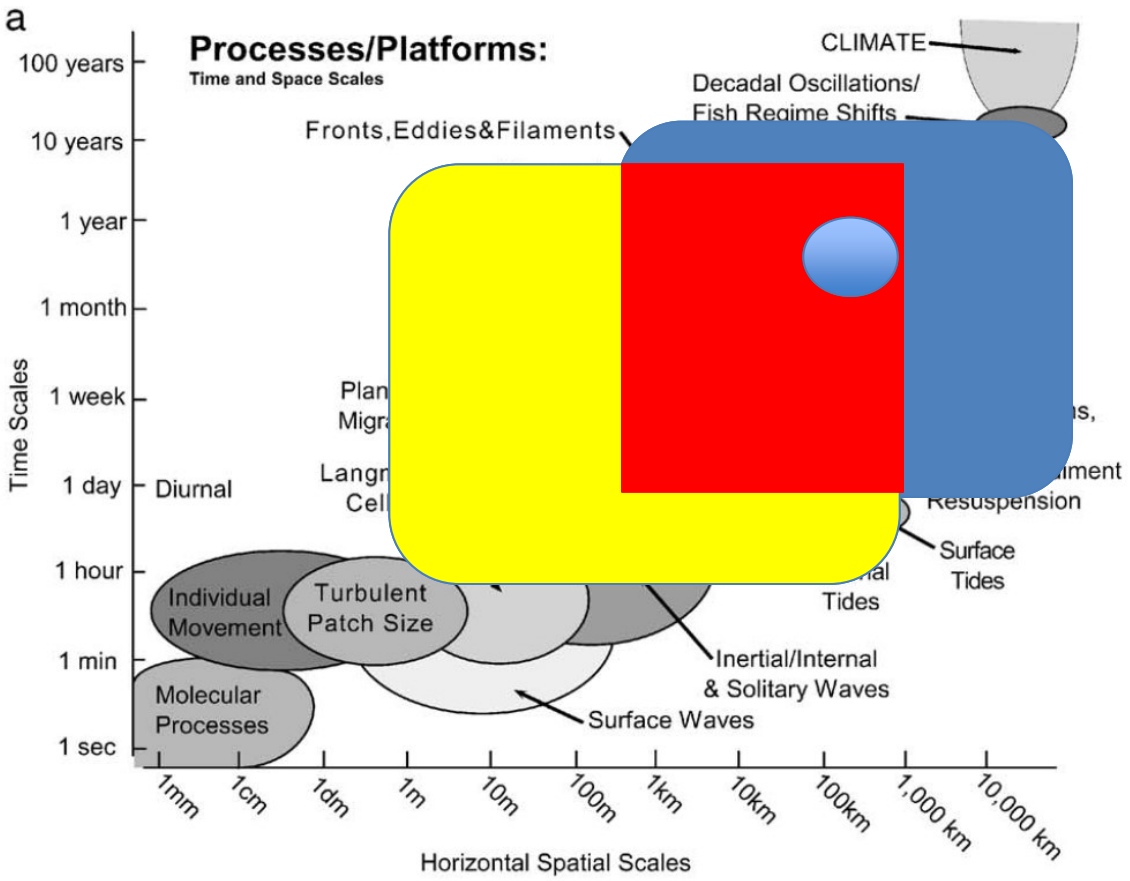


Integration



“synergetic Interplay” of the various elements



satellite

Synergetic domain

In situ platforms

Dickey, 2003

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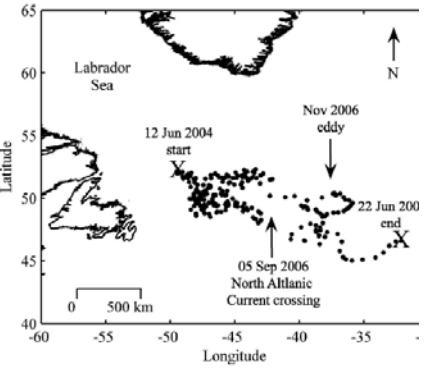
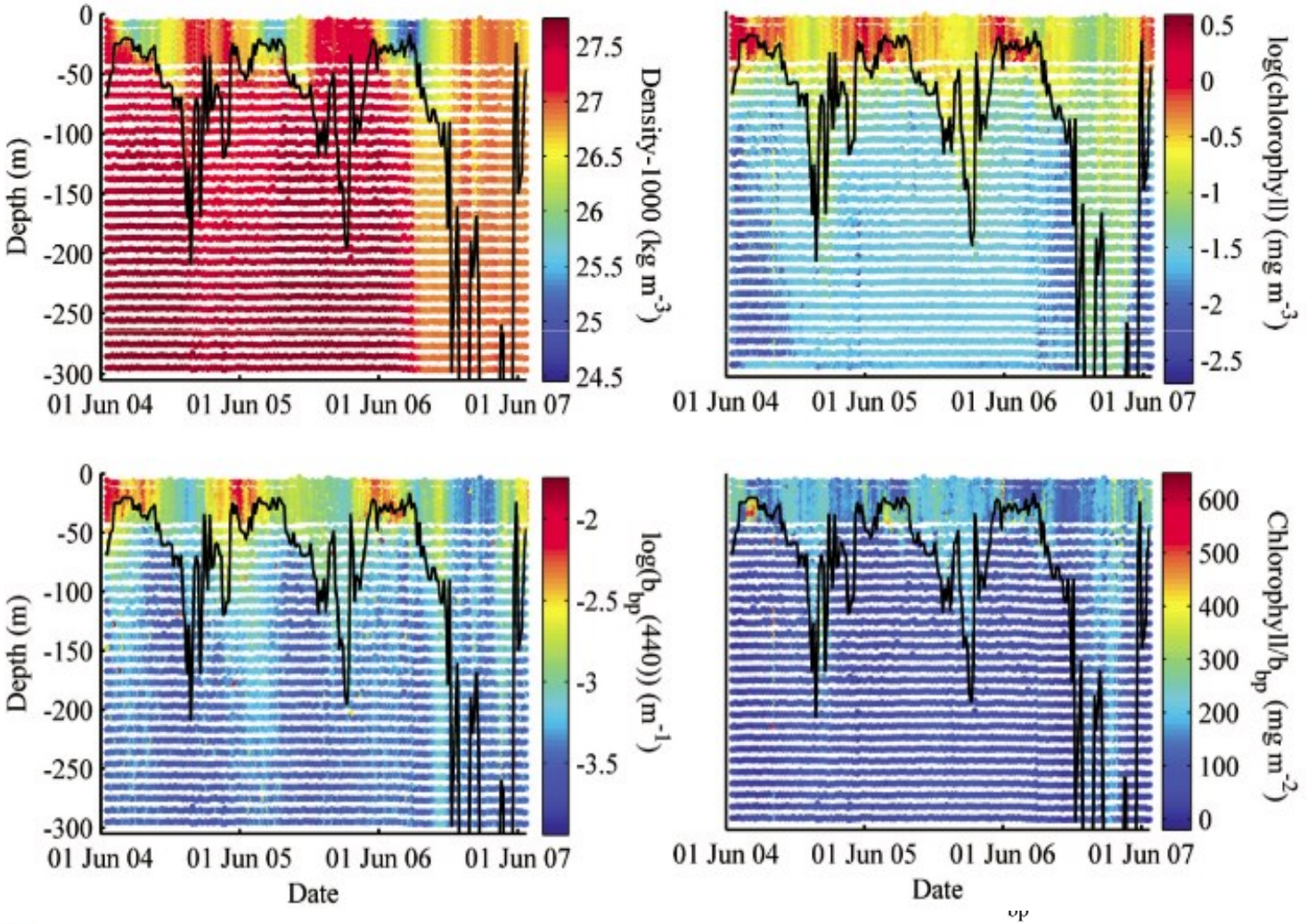
First « val » approaches and science applications



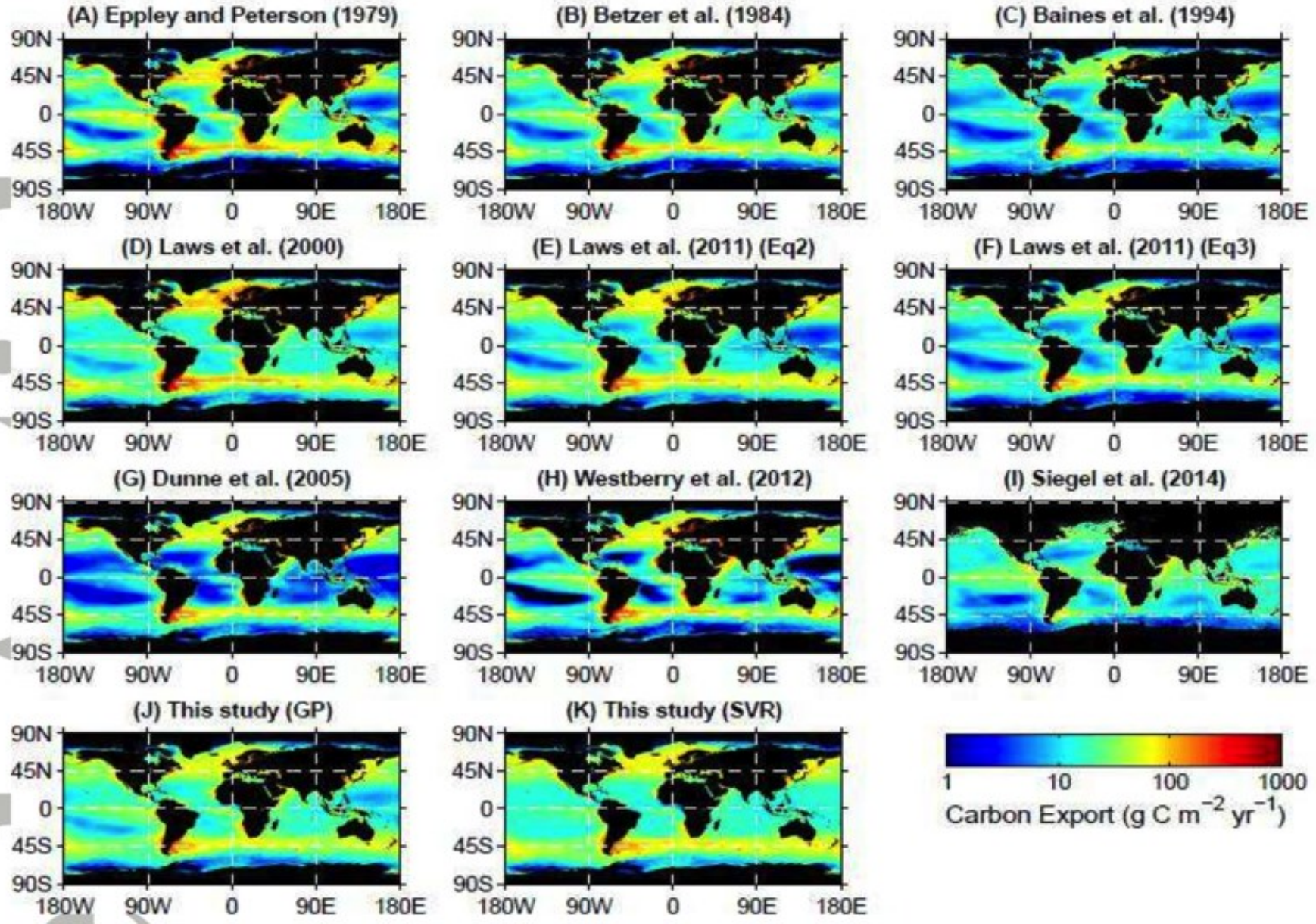


Limnol. Oceanogr., 53(5, part 2), 2008, 2112–2122
© 2008 by the American Society of Limnology and Oceanography, Inc.

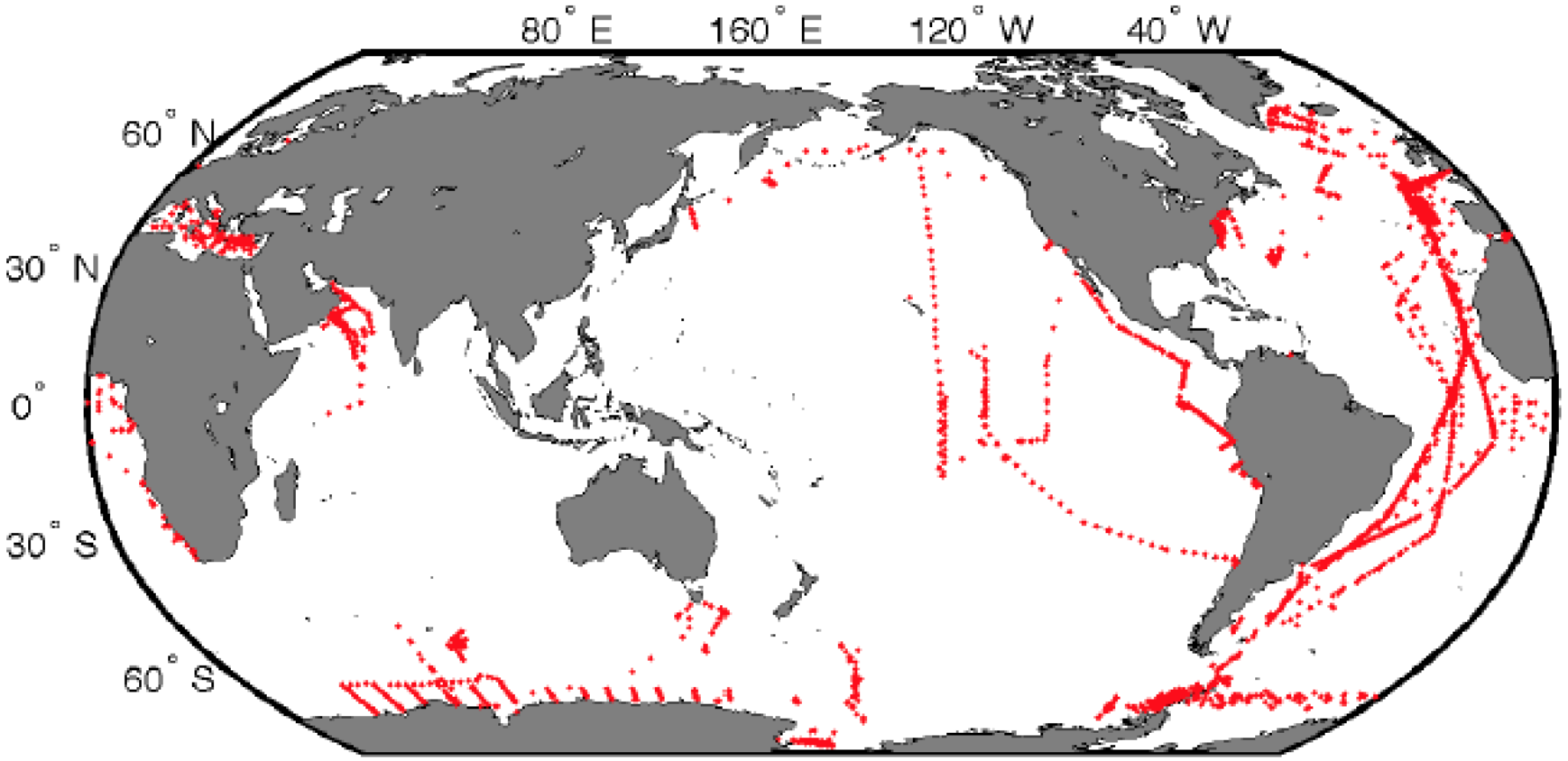
Observations of pigment and particle distributions in the western North Atlantic from an autonomous float and ocean color satellite

Boss et al., 2008

Development of « transfert functions »



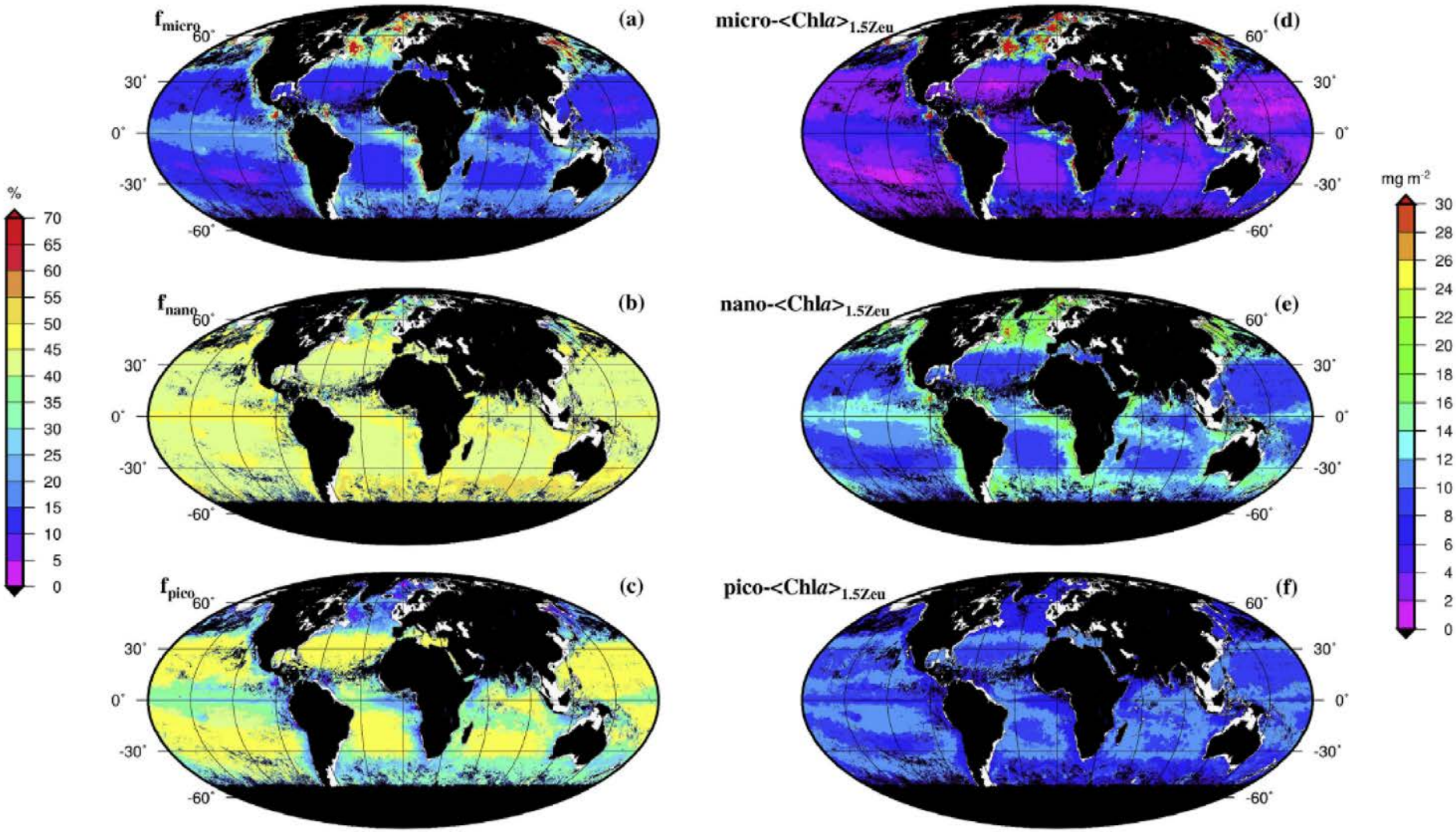
HPLC pigments data base and development of transfer functions



The MAREDAT global database of high performance liquid chromatography marine pigment measurements

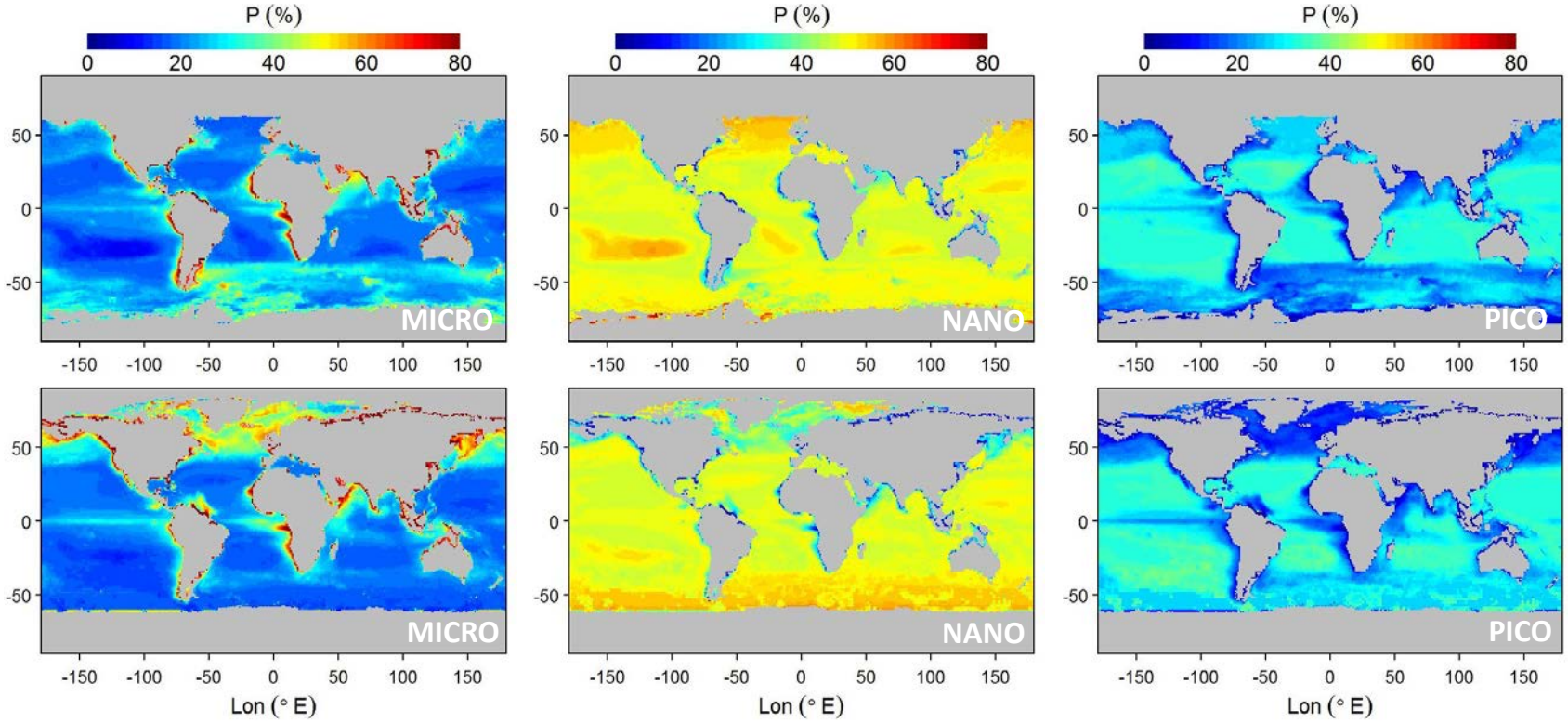
Peloquin et al., 2013: Earth System Science data

Satellite-derived group specific phytoplankton



Uitz et al. (2006). Journal of Geophysical Research, doi:10.1029/2005JC003207.

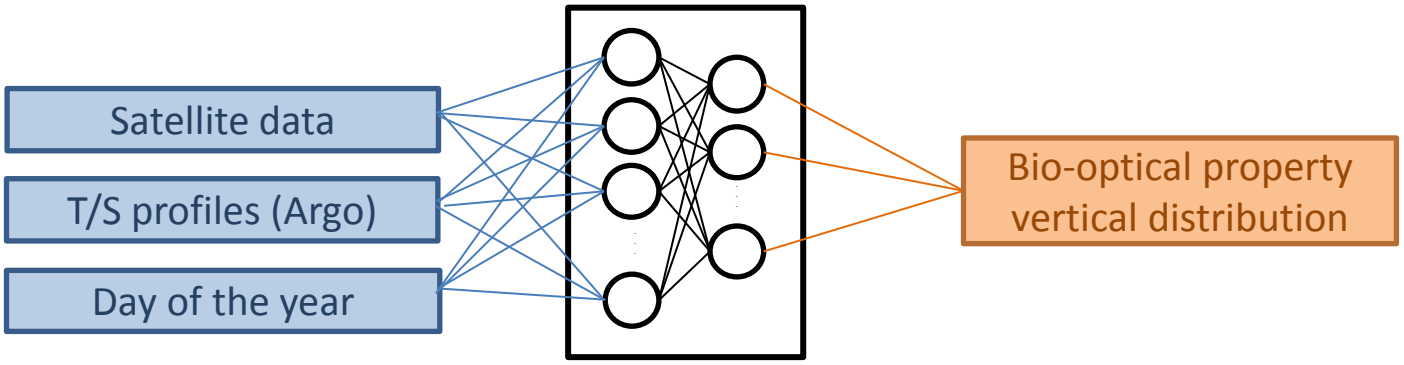
Satellite-derived phytoplankton group-specific primary production



Uitz et al. (2010). Global Biogeochemical Cycles, doi:10.1029/2009GB003680

Linking Argo TS data and satellite backscattering

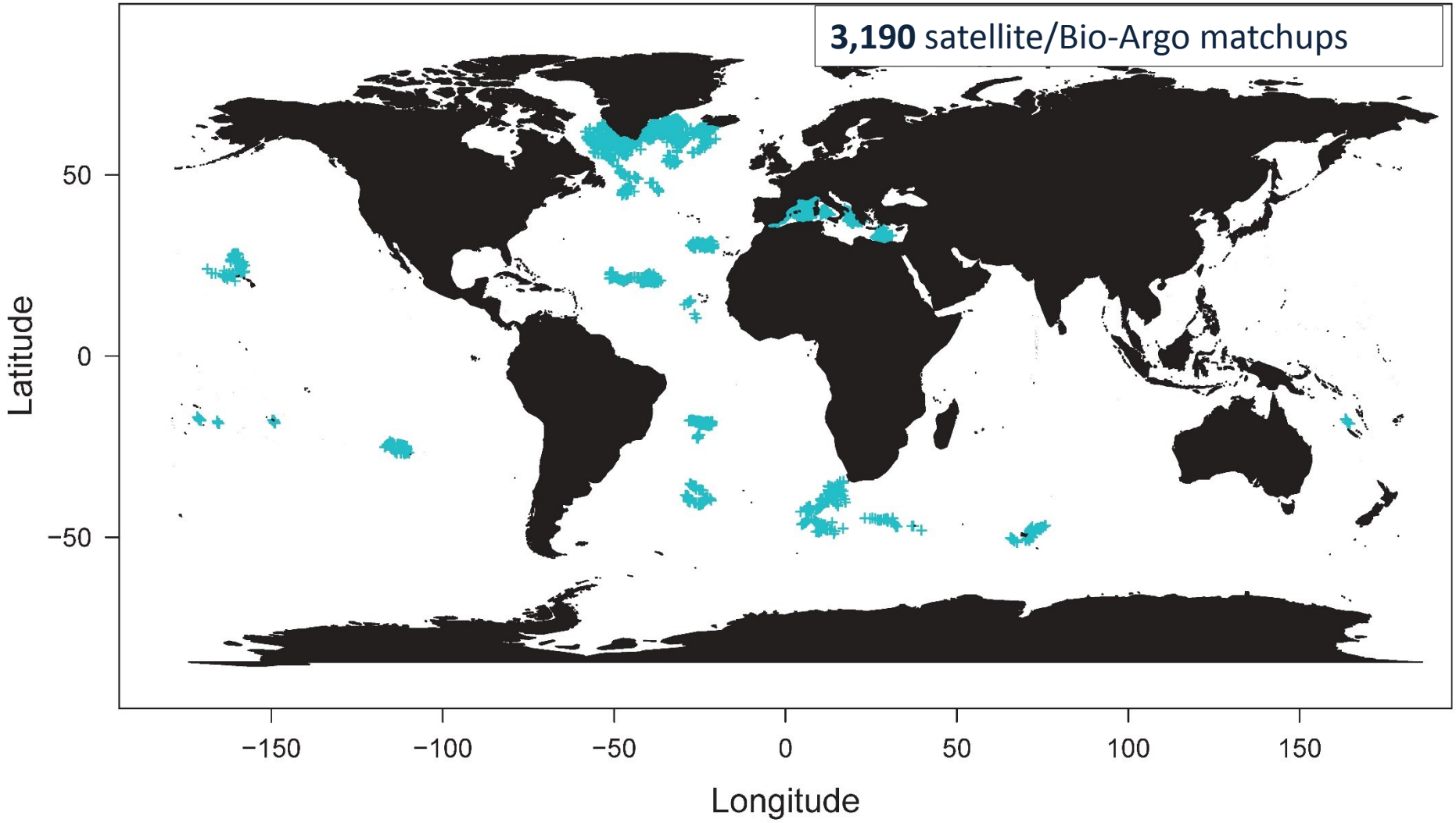
Neural network to merge ocean color and Argo data



- **Bio-Argo** data used as reference values to train and validate algorithm.
- Concurrent profiles of density and bio-optical properties essentially collected by **Bio-Argo floats**, concomitant with **satellite products** (i.e. matchups from 9-km/8-day MODIS Aqua)
- NN **training** using 80% of the database and **validation** using 20% of the database

Linking Argo TS data and satellite backscattering

Training data base: Bio-Argo



Sauzède et al, JGR 2016

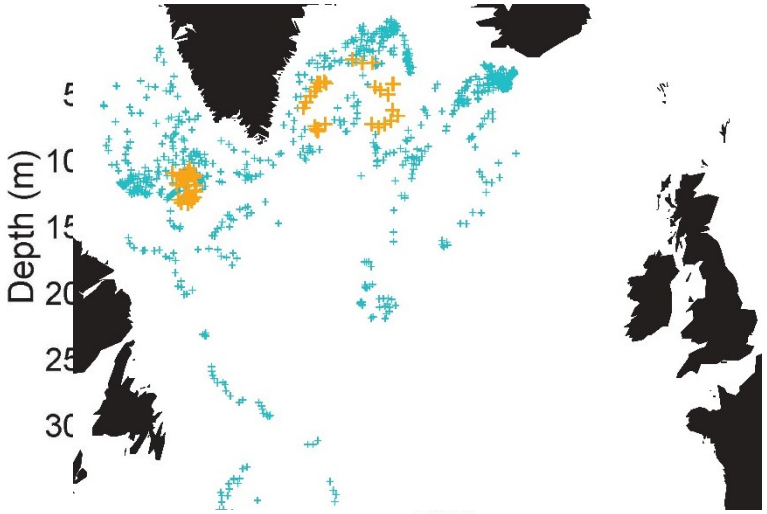
Linking Argo TS data and satellite backscattering

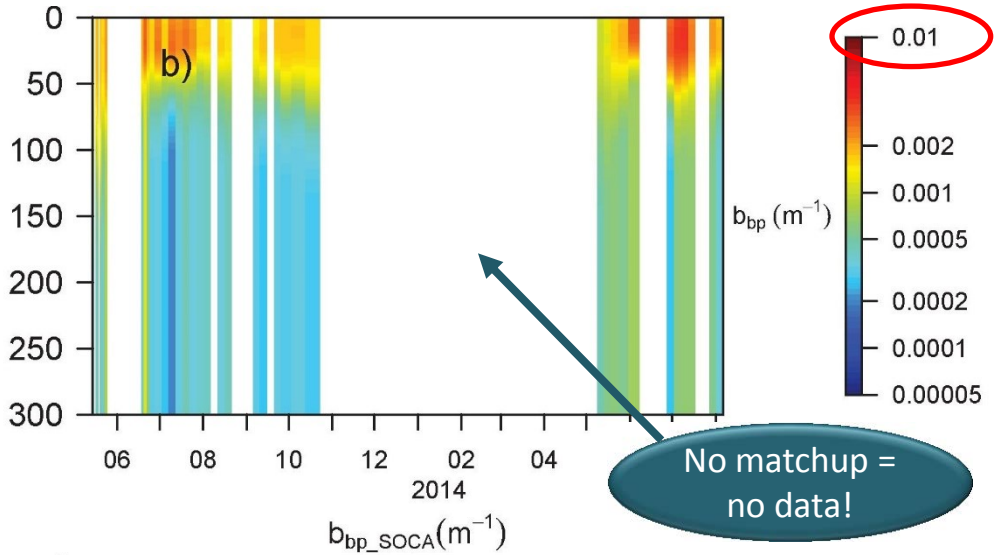
Validation using independent float data

b_{bp} from Bio-Argo floats

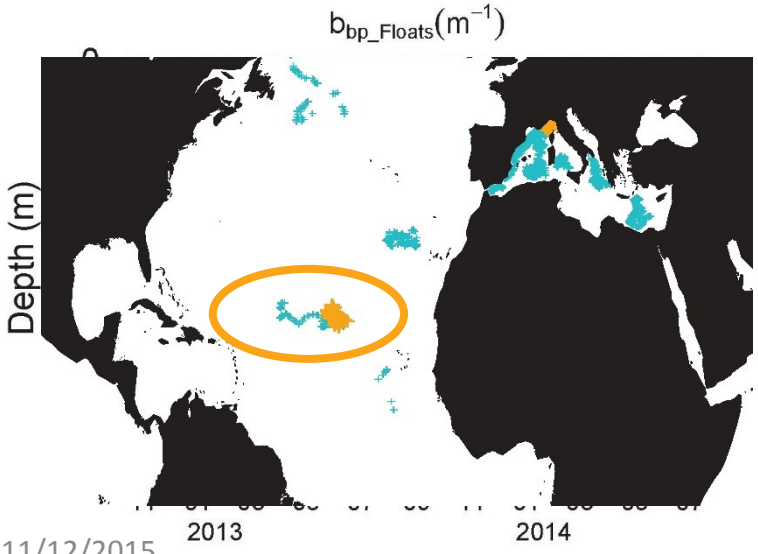
b_{bp} from SOCA:
Satellite-Bio-Argo (only T/S) matchup

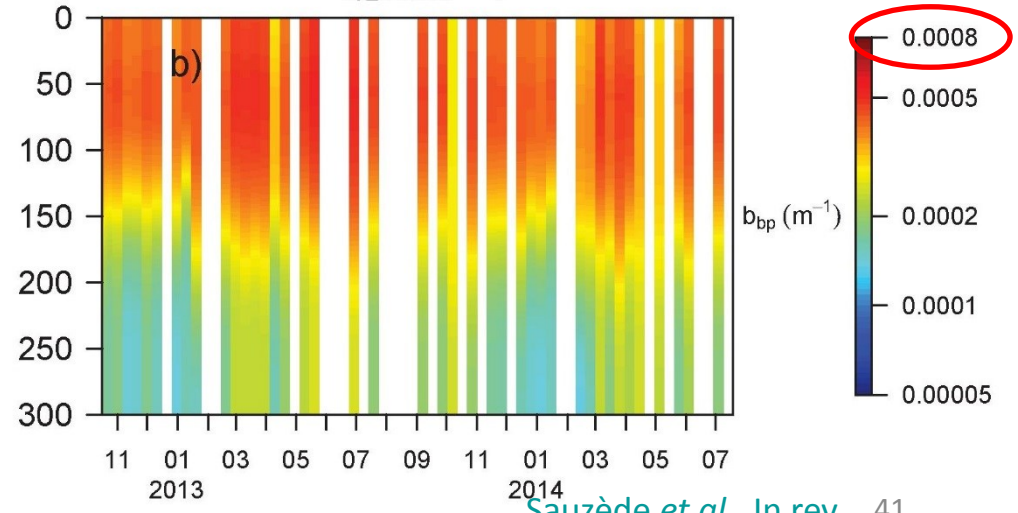
North Atlantic Supbolar Gyre





North Atlantic Subtropical Gyre





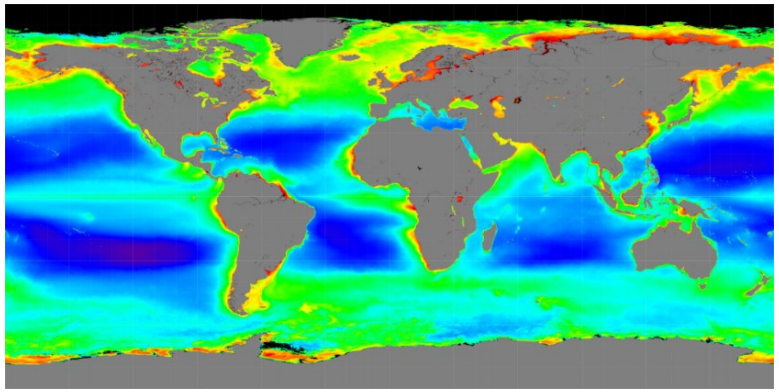
Sauzède *et al.*, In rev.

Linking Argo TS data and satellite backscattering

Building climatologies

Surface ocean color climatologies

Argo T/S climatology (Roemmich and Gilson ,2009)



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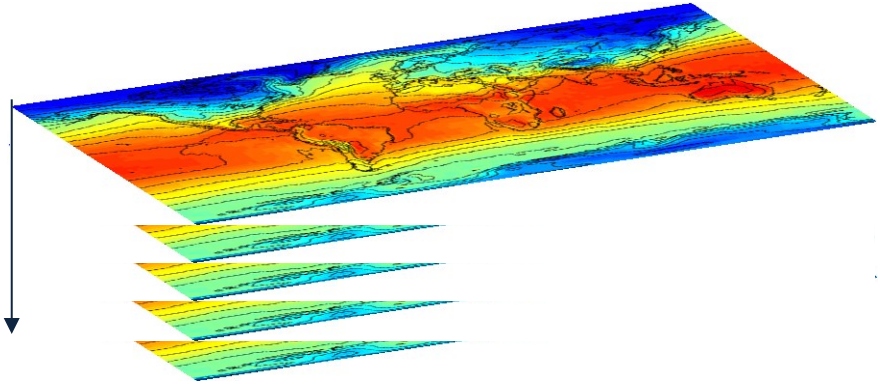
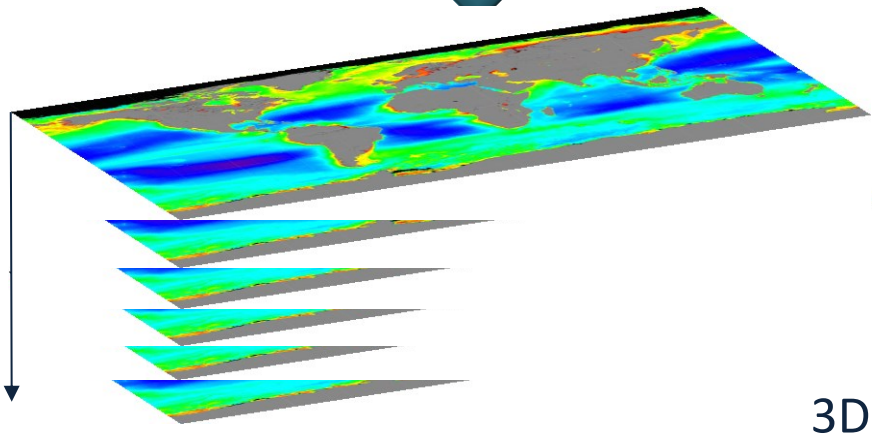


SOCA-BBP



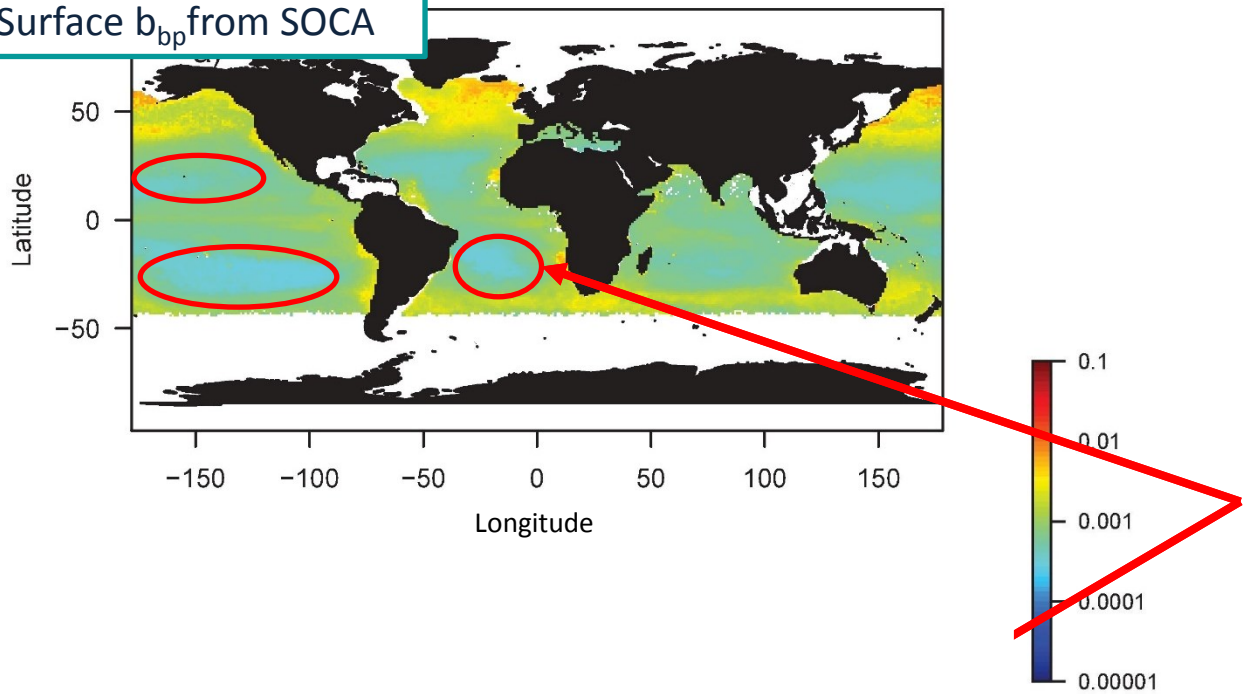
3D global climatology of b_{bp}

Sauzède et al, JGR 2016

Linking Argo TS data and satellite backscattering

Merged product better than OCR remote sensing alone?

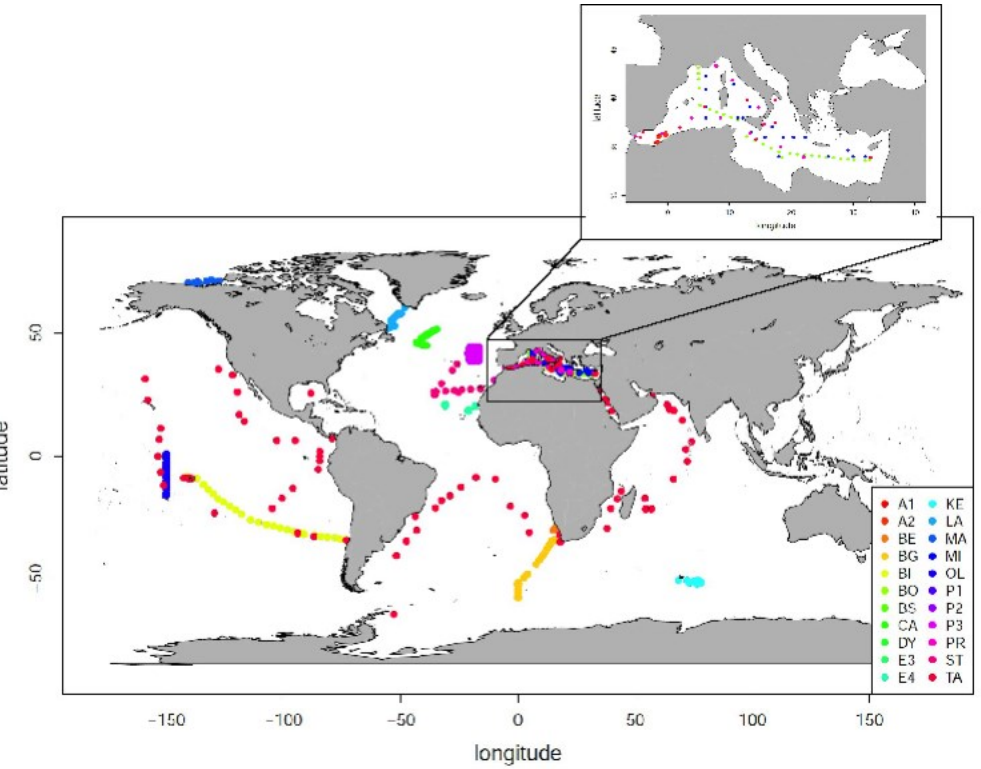
Surface b_{bp} from SOCA



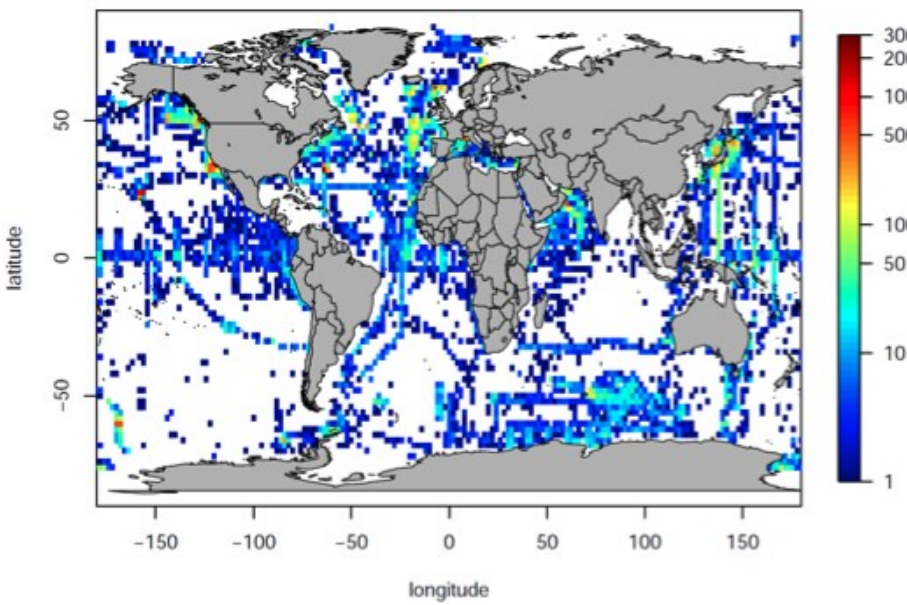
Overestimation of b_{bp} from satellite estimations: e.g. Brown *et al.,* 2008; Lee and Huot, 2014

Sauzède et al, JGR 2016

Neural network techniques to be applied to fluorescence data base and later to remote sensing: retrieval of the vertical profile of Chla and of main group-specific phytoplankton



- ~ 900 HPLC profiles acquired over ~ 20 years

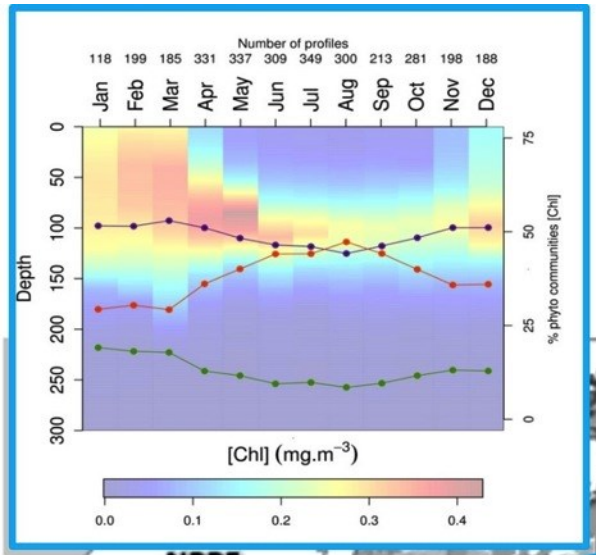


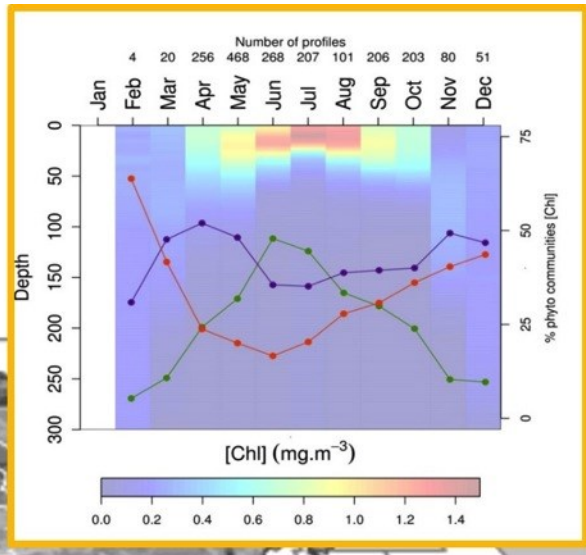
- ~ 40,000 Chla fluorescence profiles over 1970-2012.
- un-calibrated profiles.
- Scattered in various databases

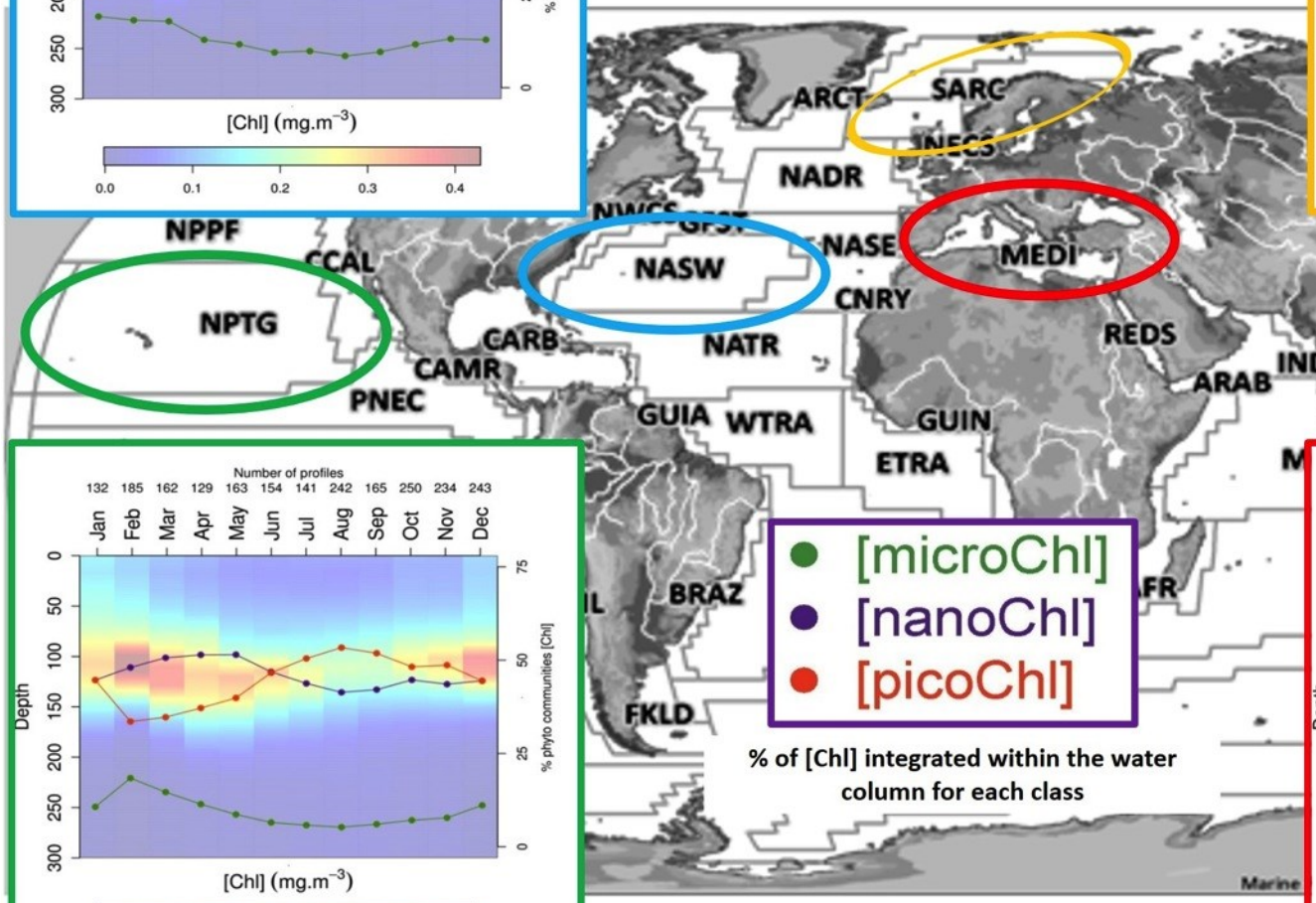
Sauzède et al., JGR, 2015

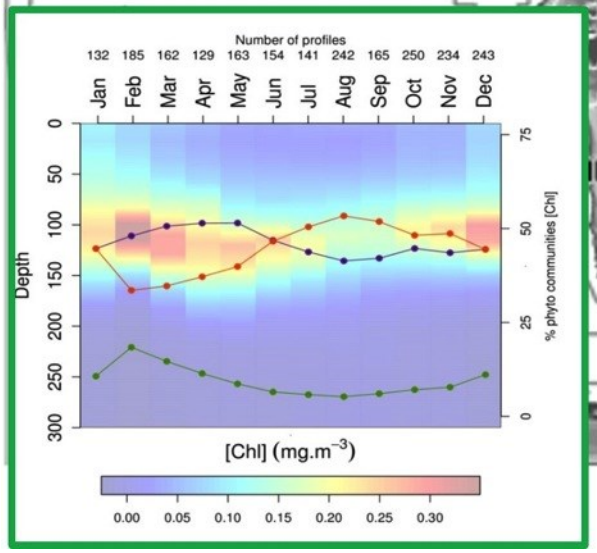
Application of the method to historical fluorescence data bases

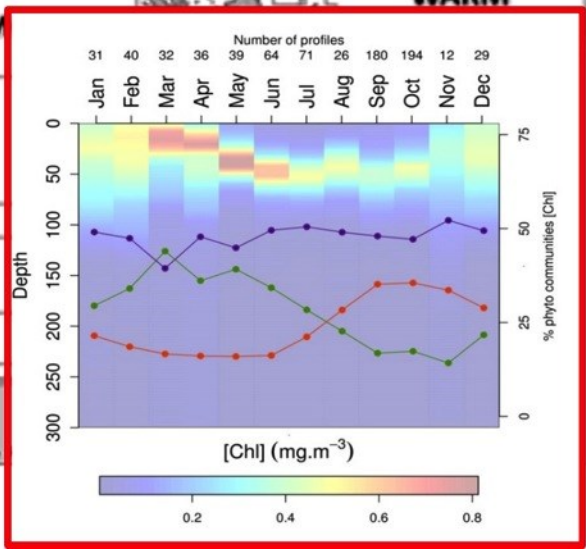
Regional climatologies





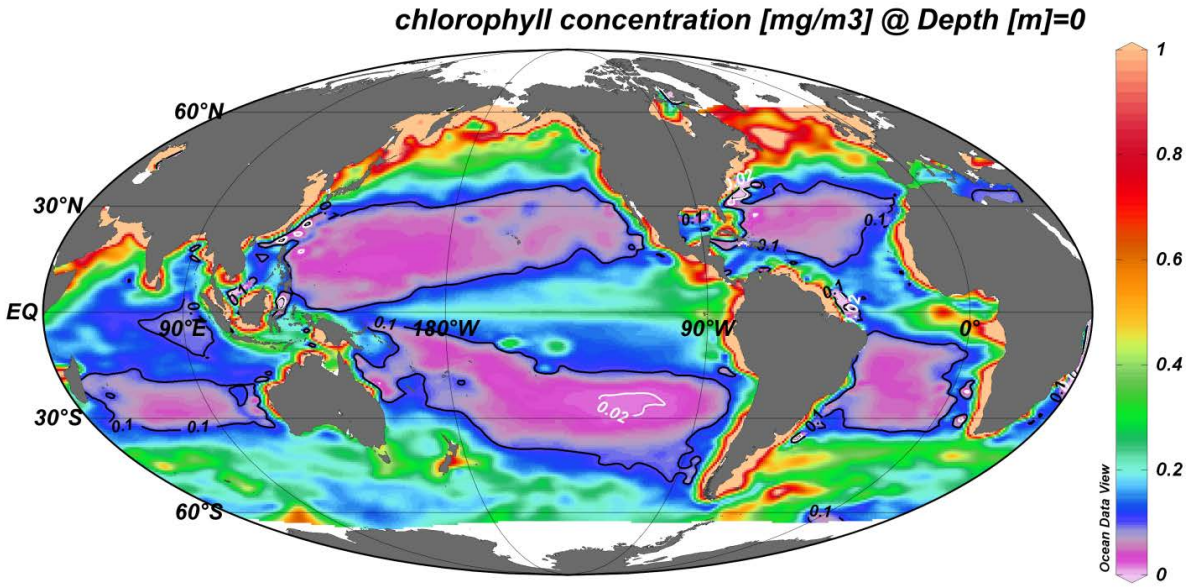


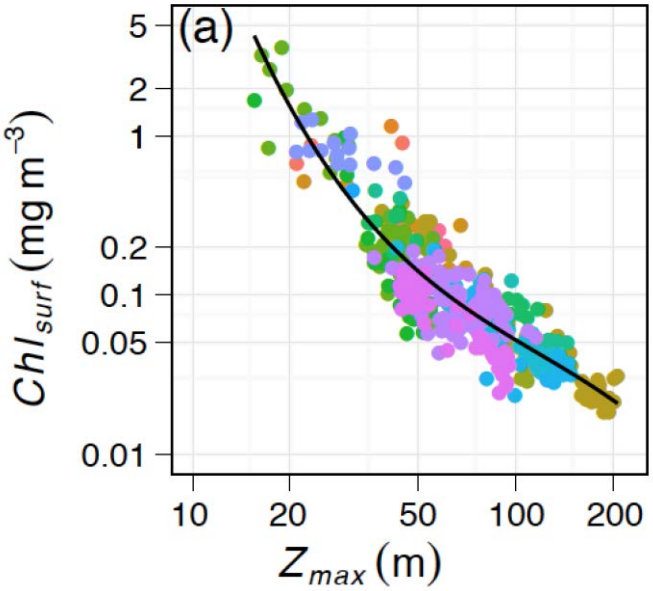


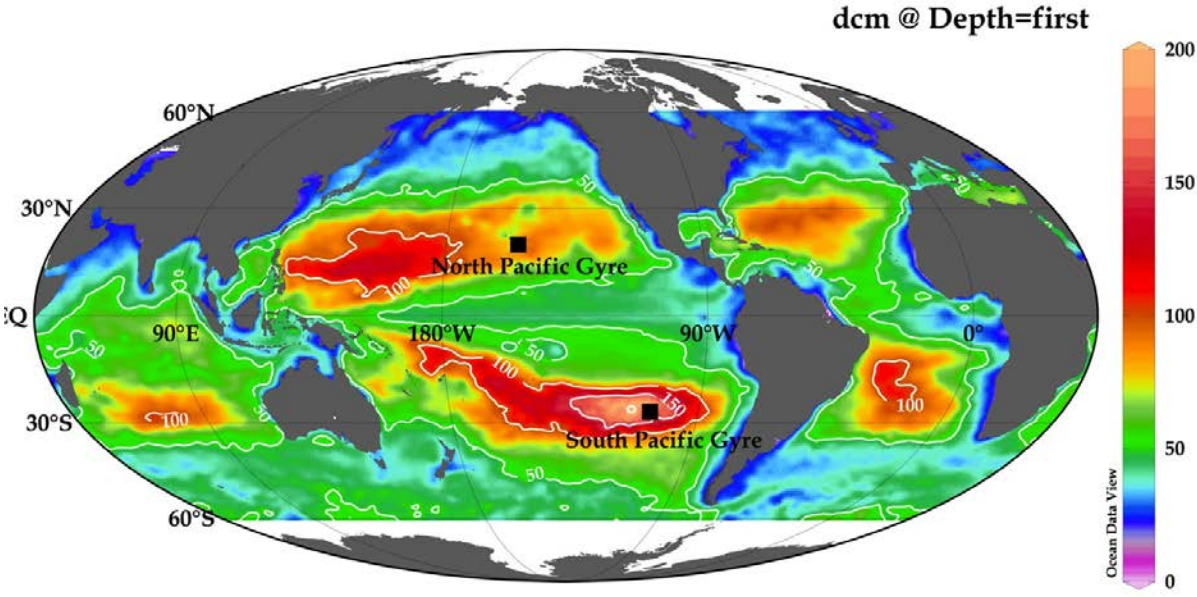


Sauzède et al., ESSD 2015

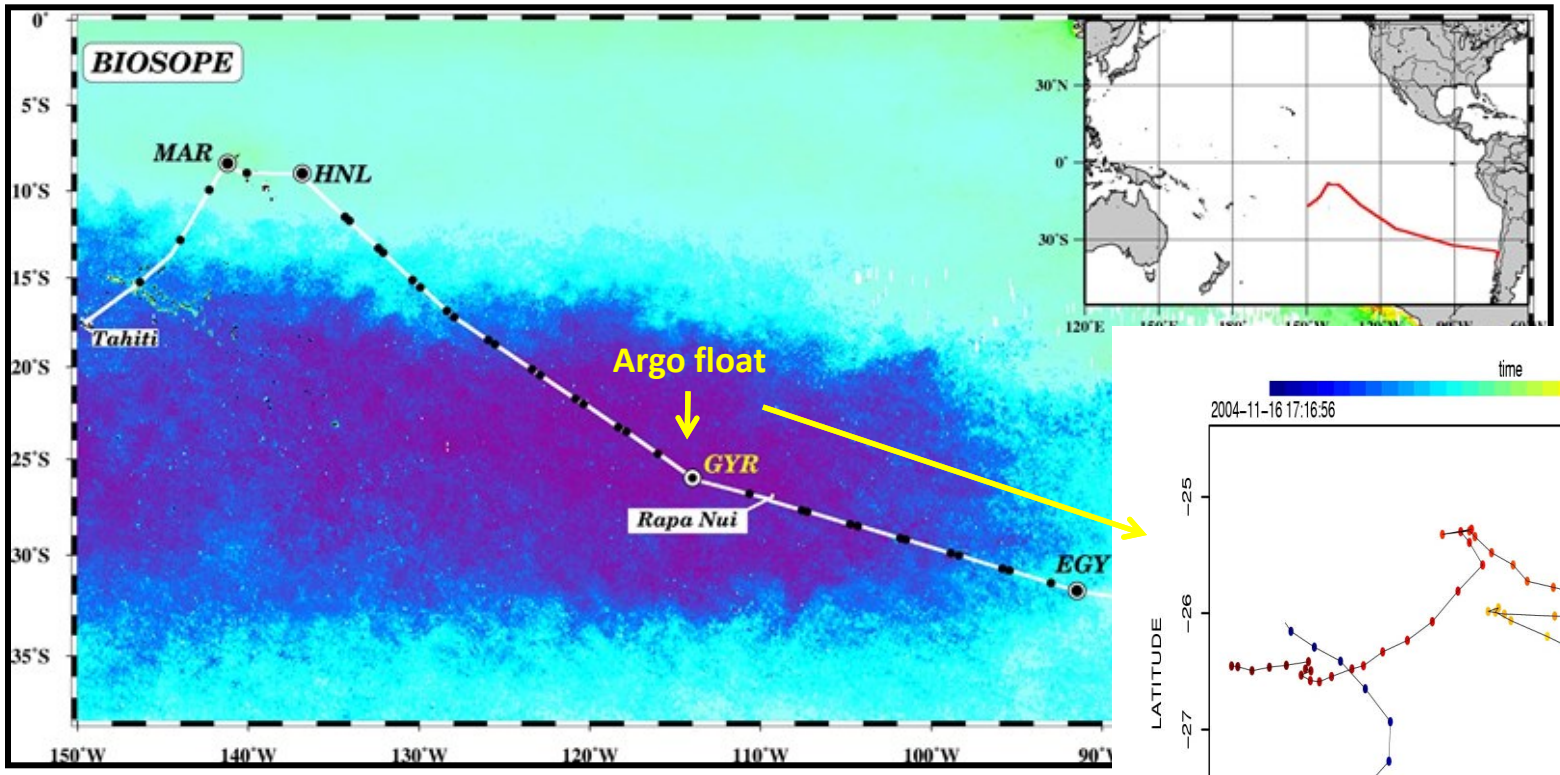
Linking DCM depth to surface Chla

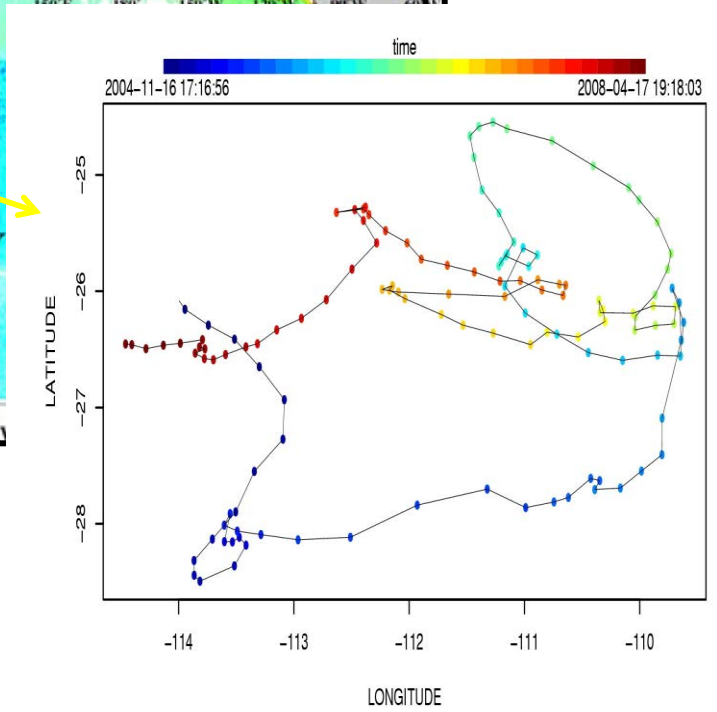




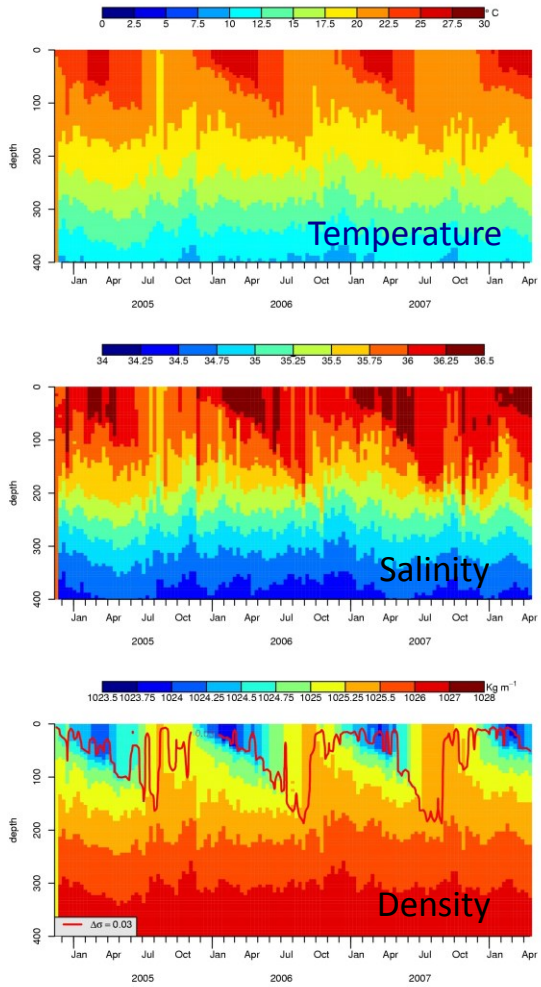


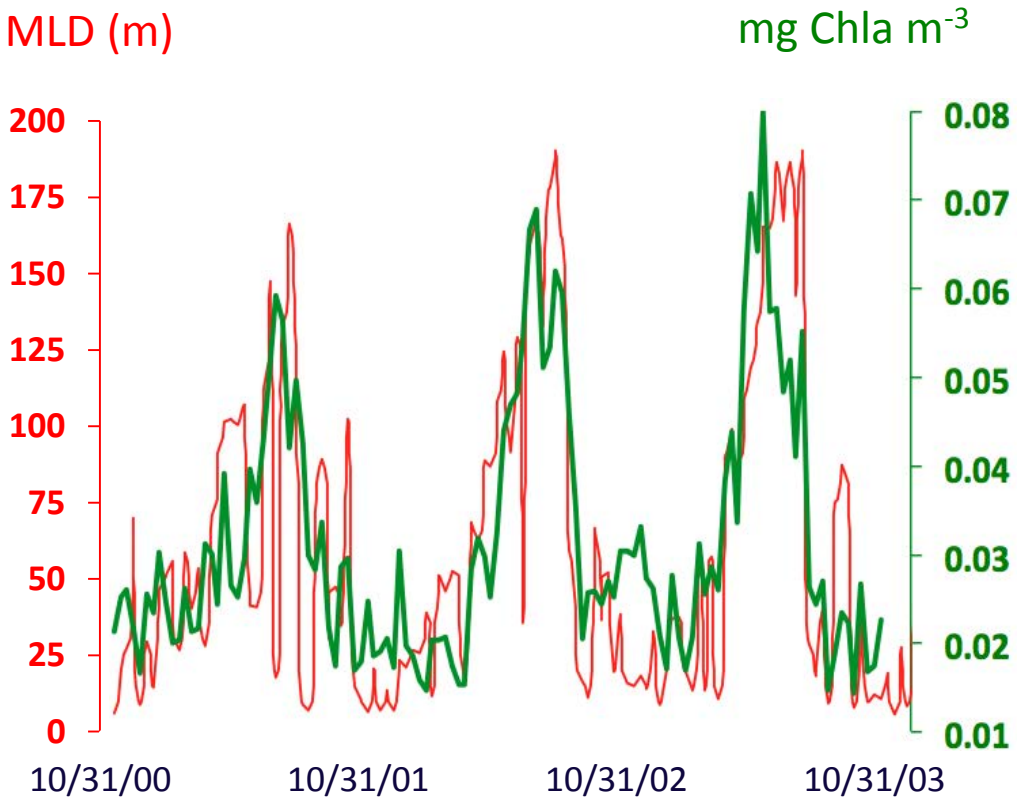
Surface Chla dynamics in subtropical gyre: satellite Argo approach





Surface Chla dynamics in subtropical gyre: satellite Argo approach





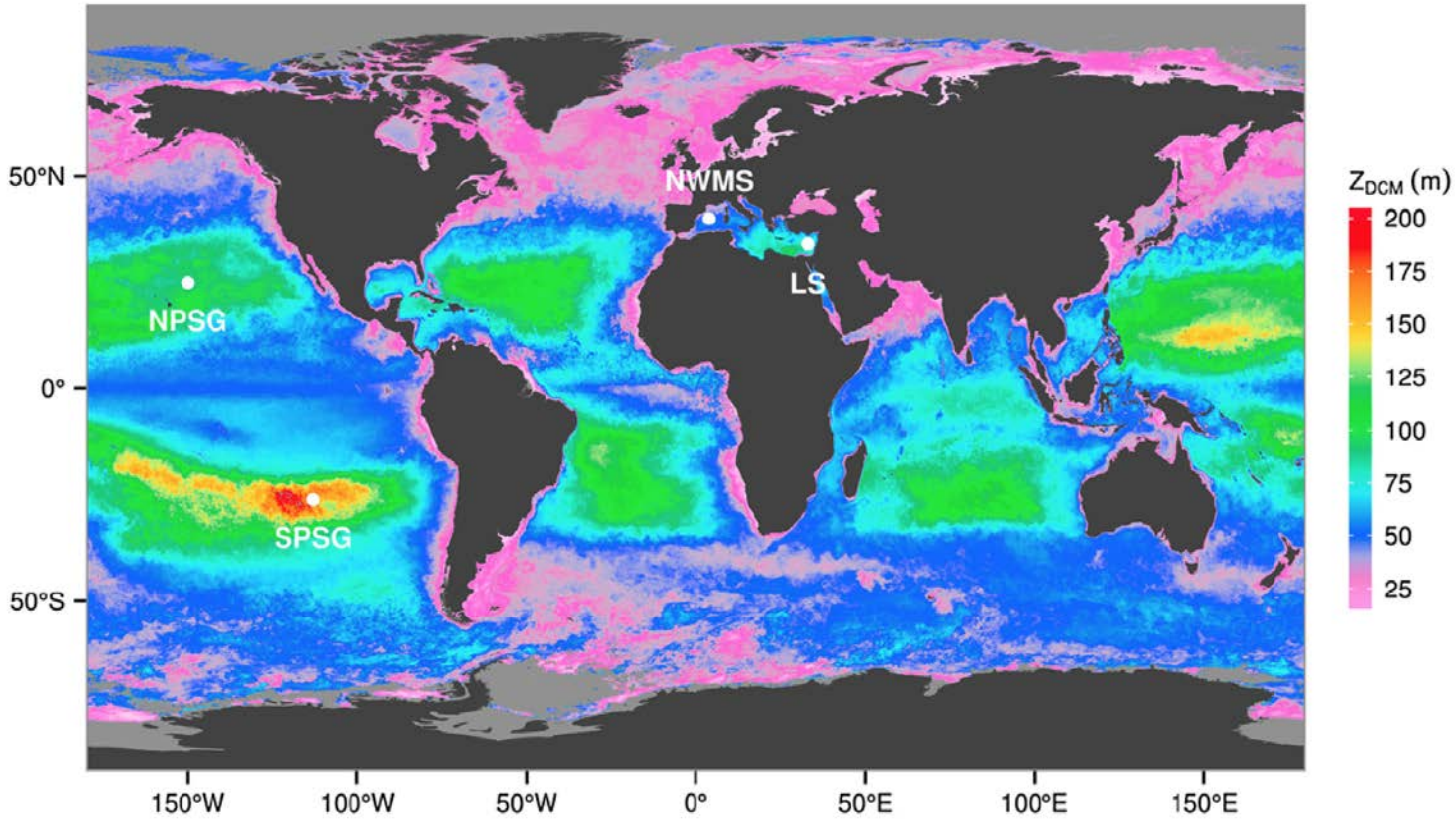
See IOCCG report (2011)

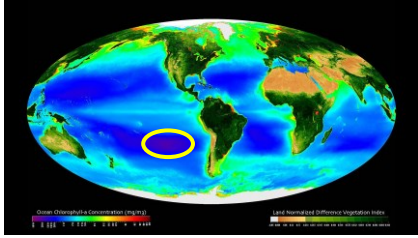
Understanding the seasonal dynamics of phytoplankton biomass and the deep chlorophyll maximum in oligotrophic environments: A Bio-Argo float investigation

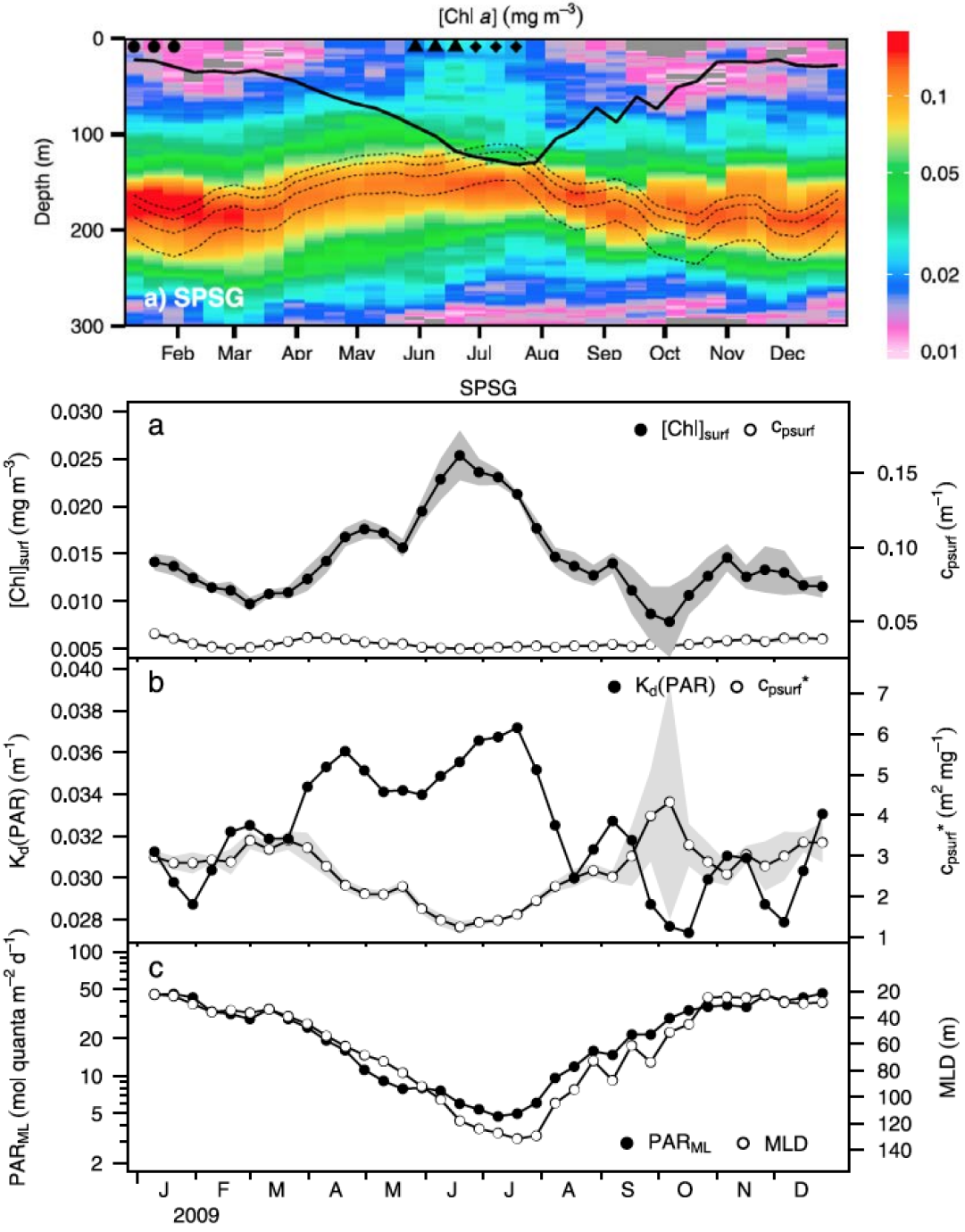
AGU PUBLICATIONS

Global Biog

Alexandre Mignot[1,2,3], Hervé Claustre[1,2], Julia Uitz[1,2], Antoine Poteau[1,2], Fabrizio D'Ortenzio[1,2] and Xiaogang Xing[4]



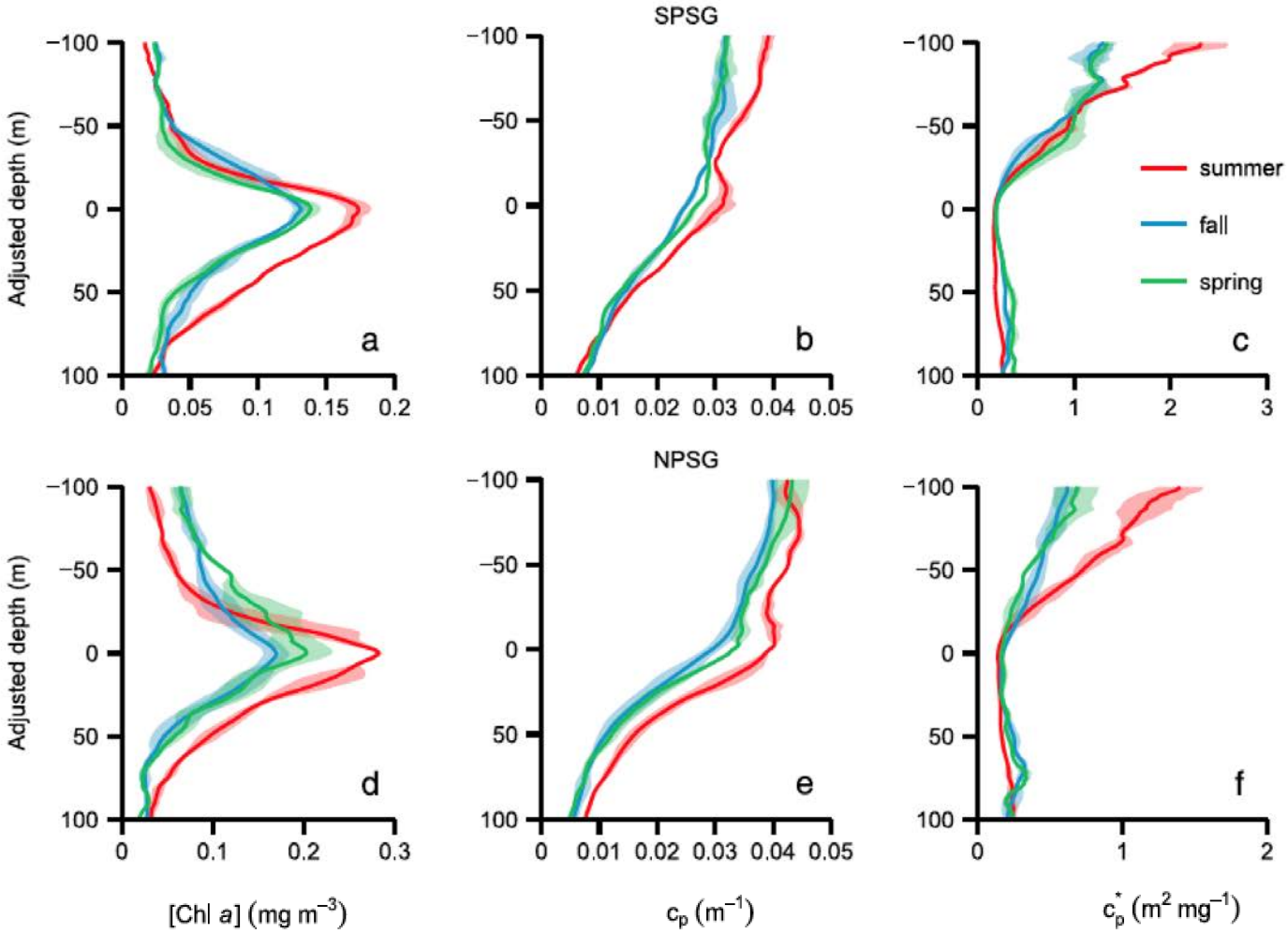




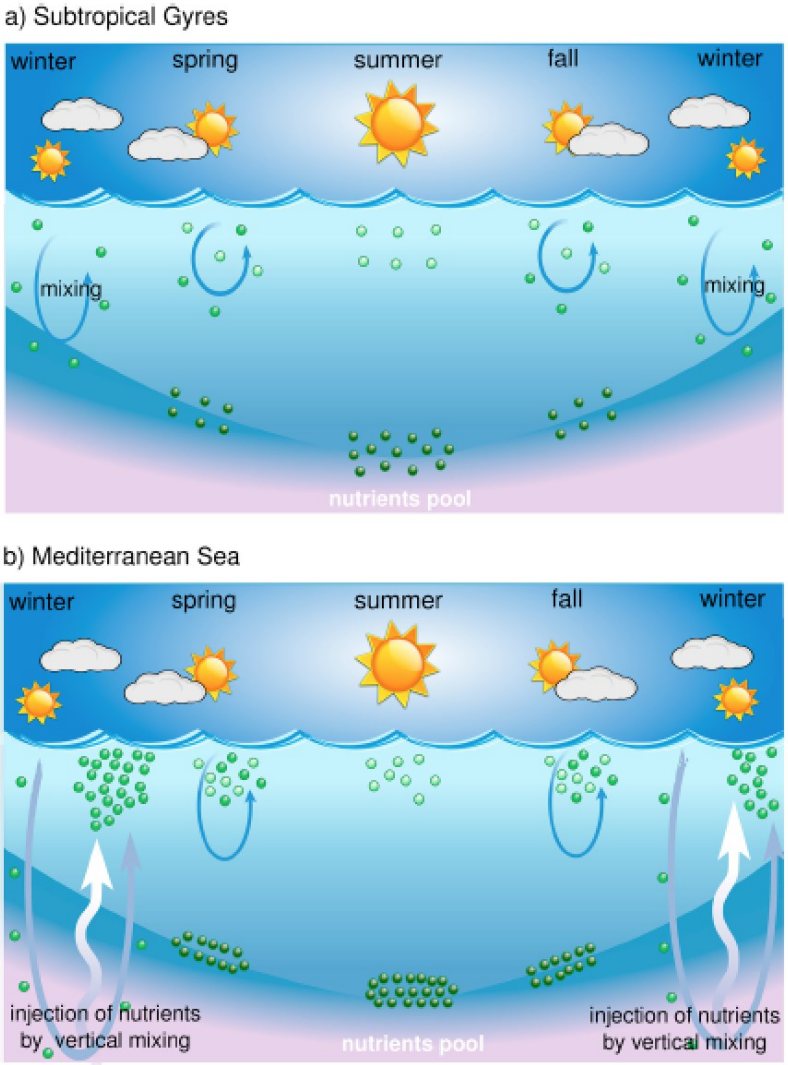
- **Winter increase in surface chla**
- **The DCM follows the isolumes**
- **The MLD is always above the nitracline depth (not shown)**

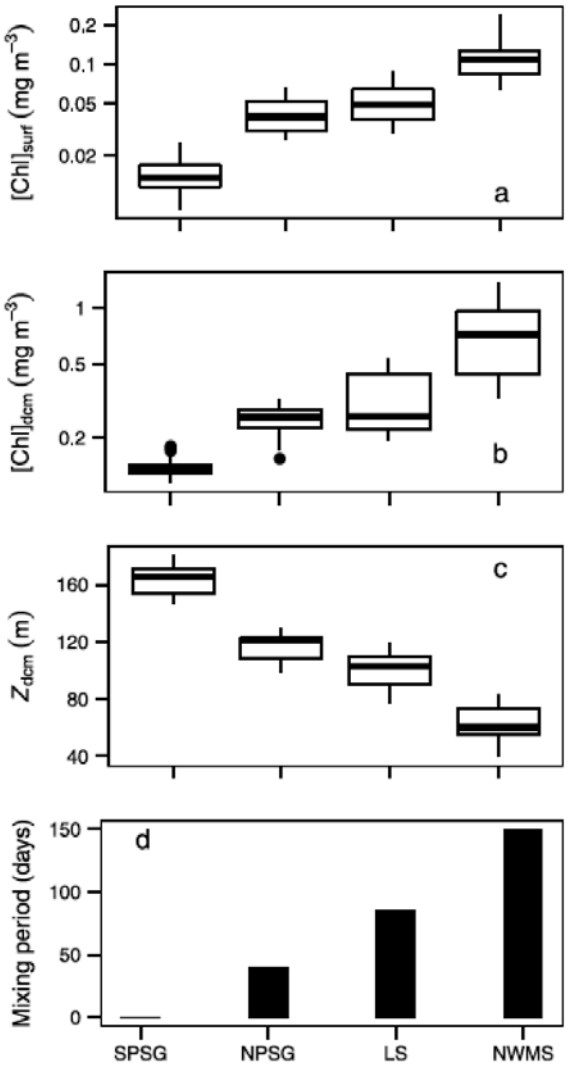
Mignot *et al.*, GBC, 2014

Seasonal variation of DCM and associated biomass proxies



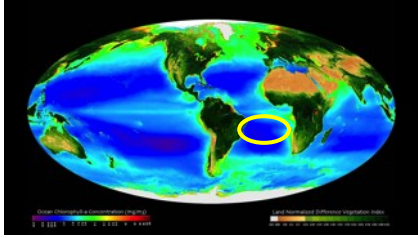
Conceptual scheme of phytoplankton dynamics in various oligotrophic environments

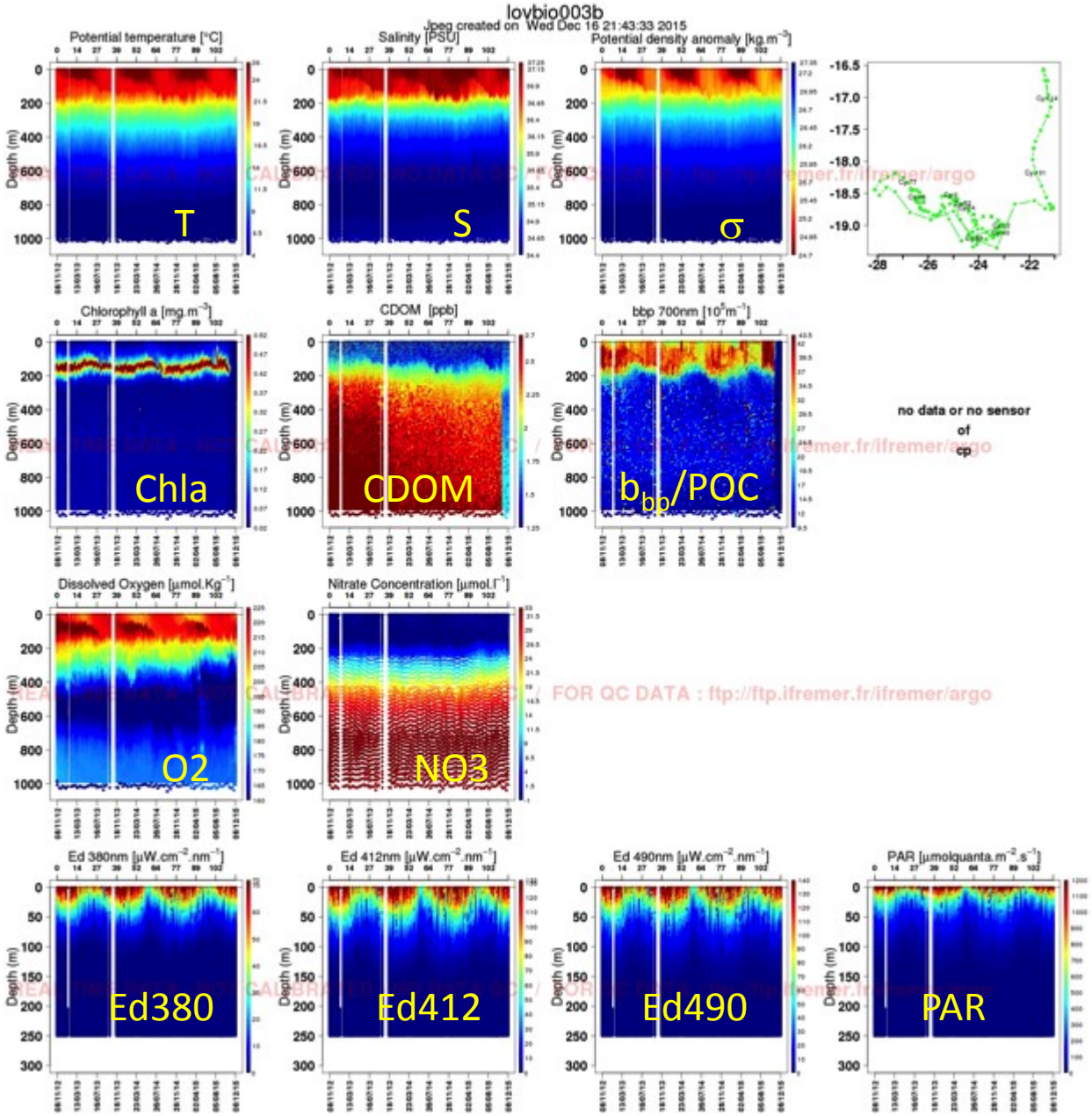




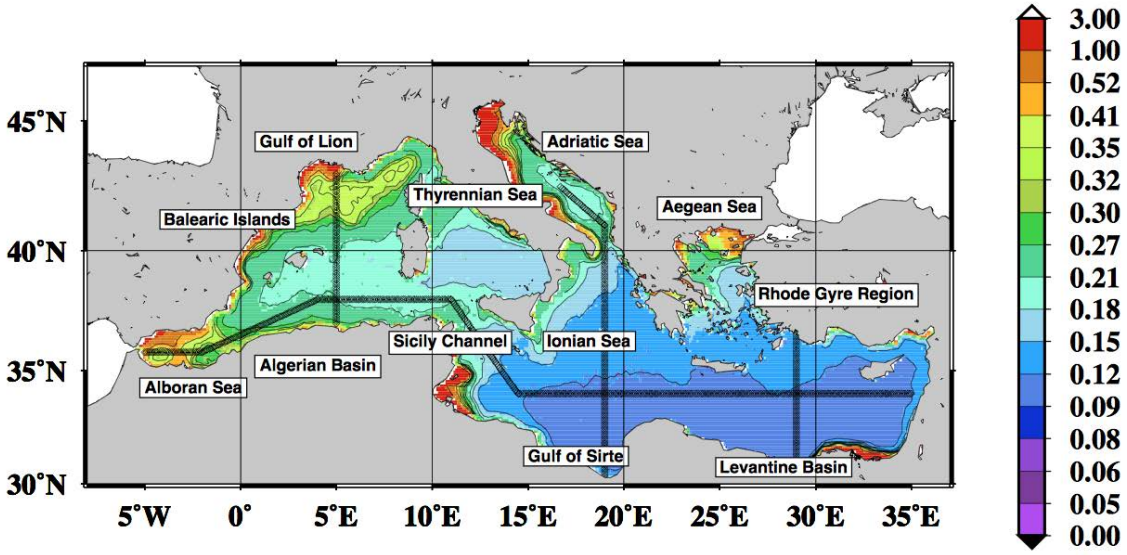
Mignot *et al.*, GBC, 2014

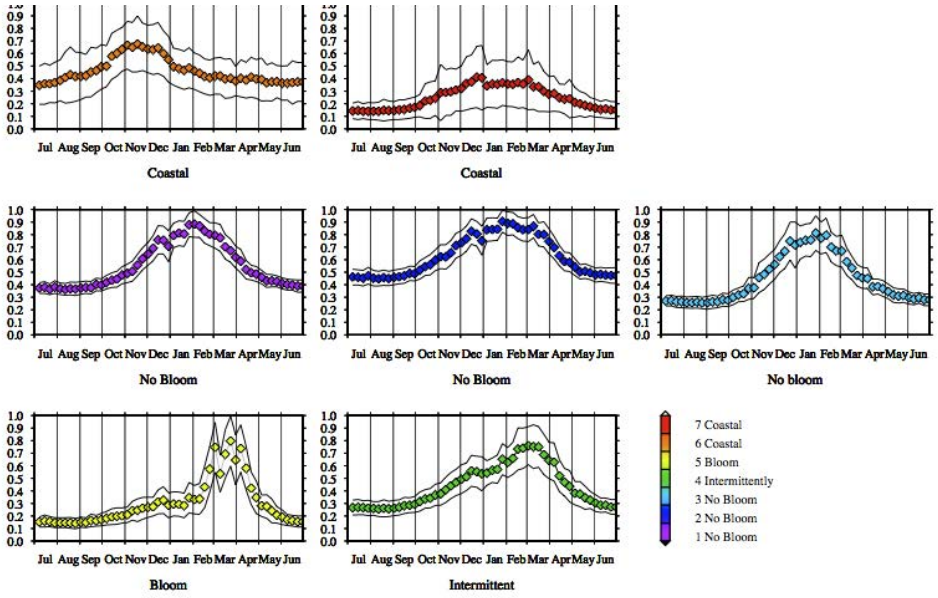
Example of (on-going) time serie
South Atlantic subtropical gyre

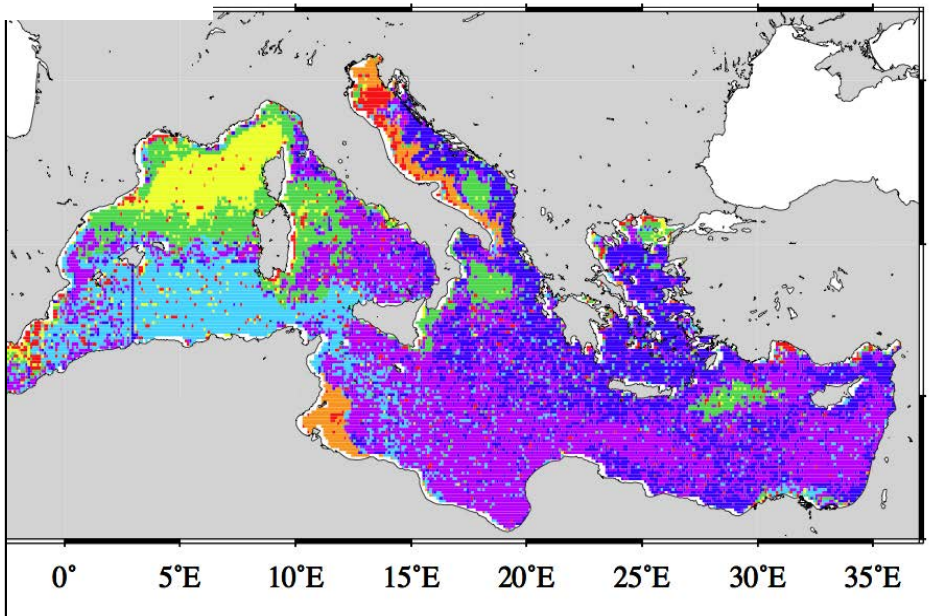




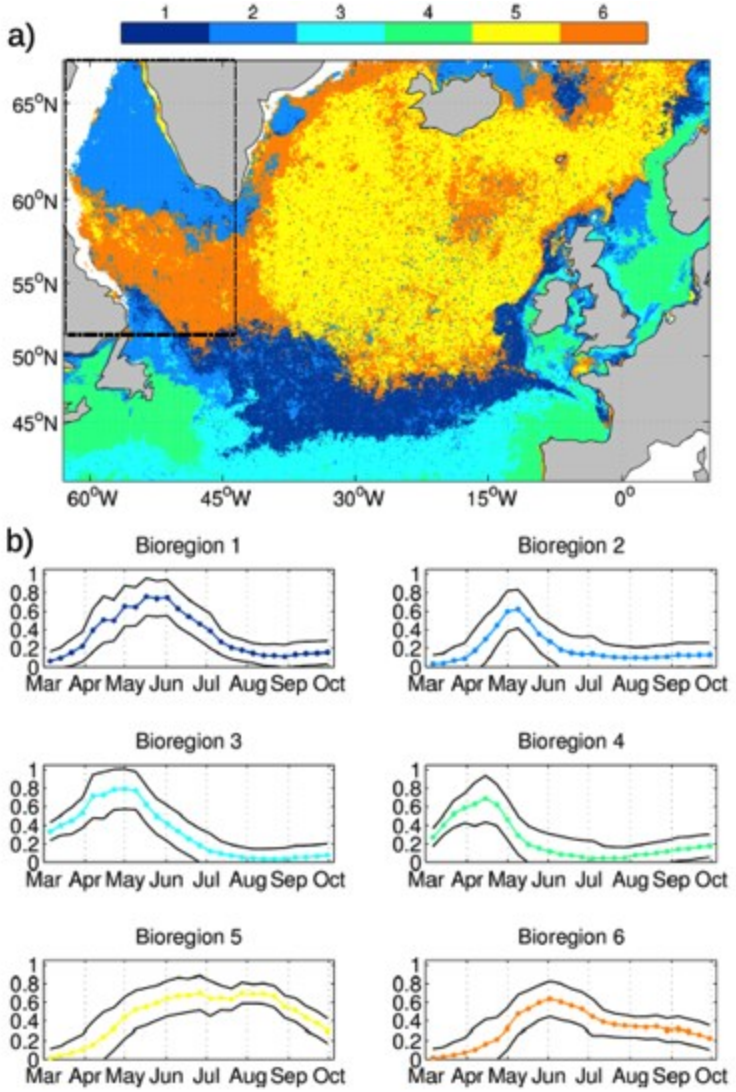
Remote sensing of OCR to define Bio-Regions and subsequent deployment strategies

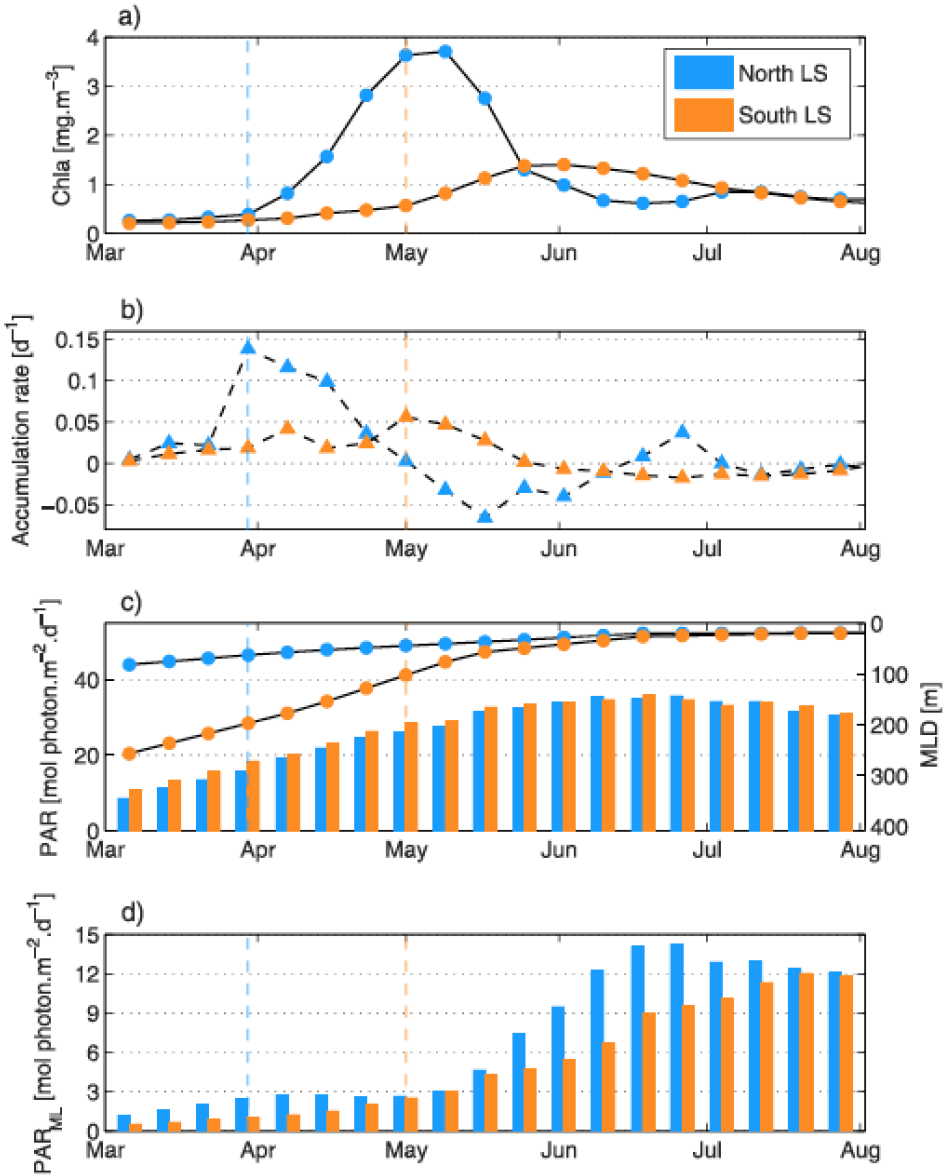






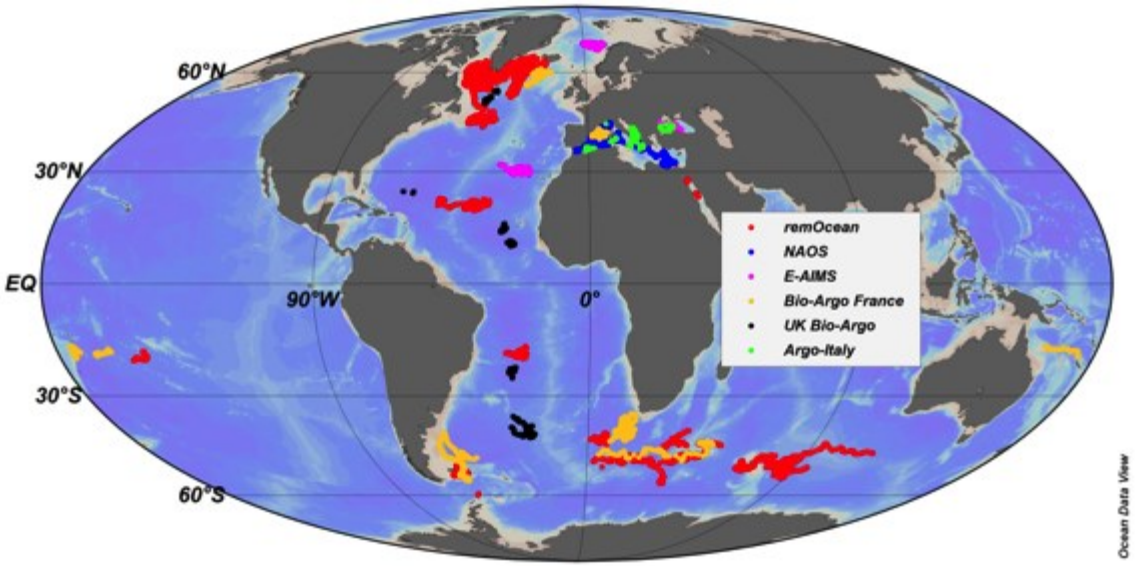
Bloom Timing and magnitude in the Labrador Sea: climatological / bioregionalisation satellite / in situ approach





Lacour et al., GRL, 2015

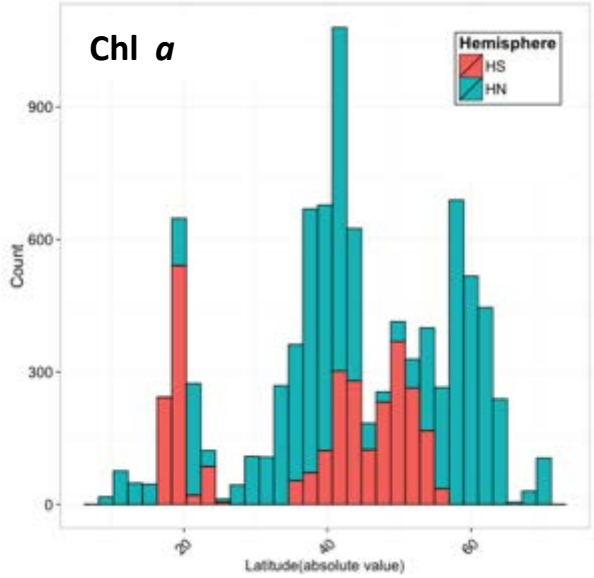
Bio-Argo floats help exploring several regions simultaneously, at high frequency and in a short time

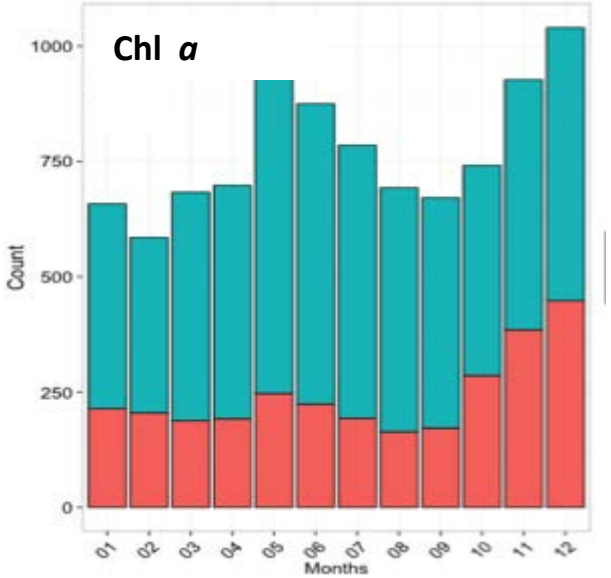


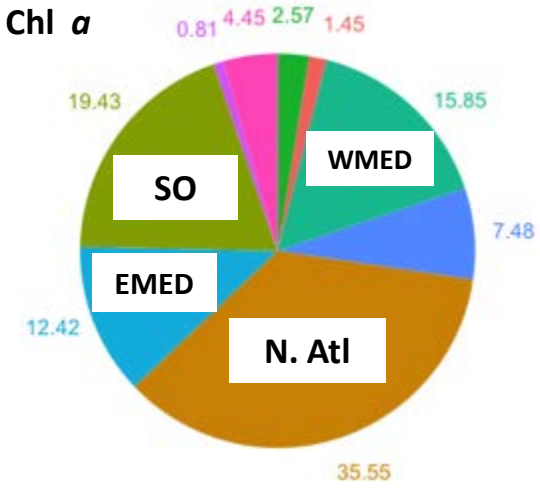
105 Bio-Argo floats

from November 2012

to January 2016

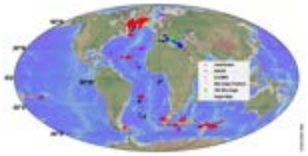




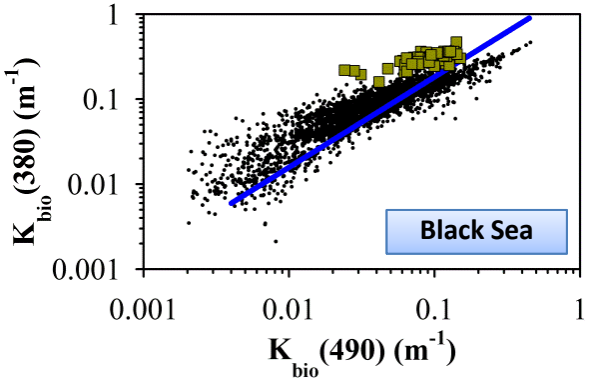


Organelli et al. (in preparation)

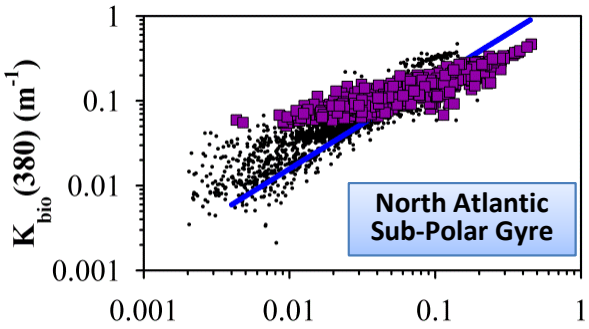
Regional vs Global

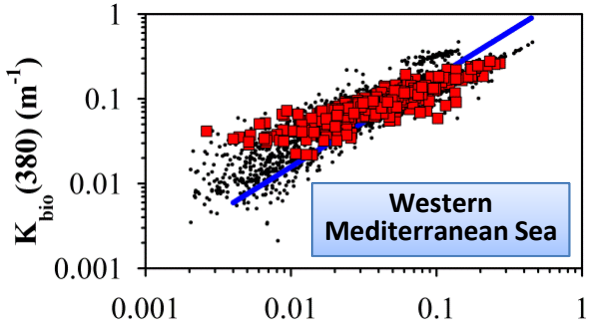


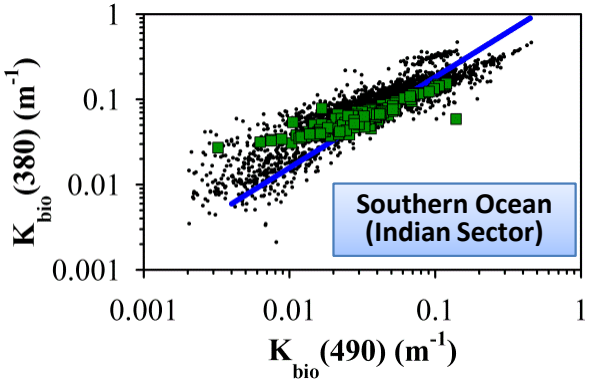
Case 2 Waters

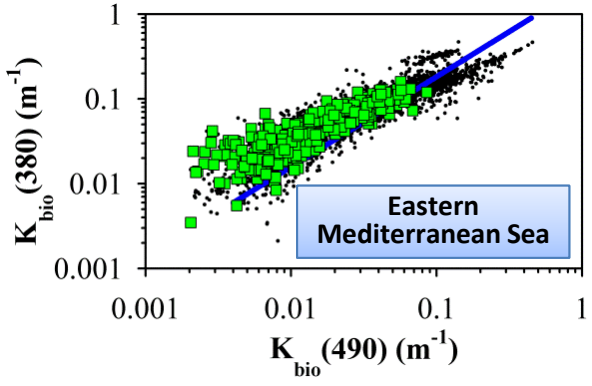


High Latitude & Temperate Seas





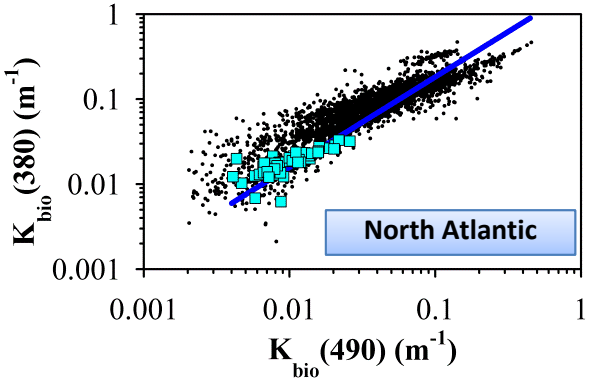


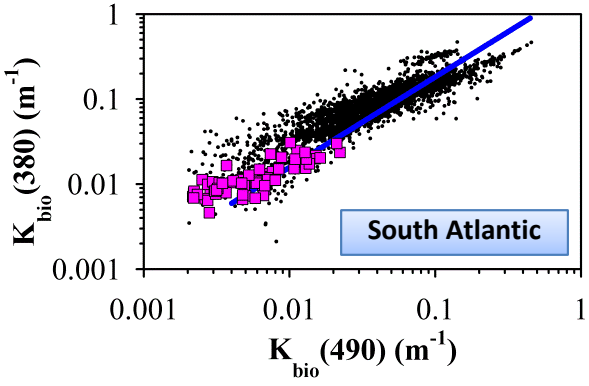


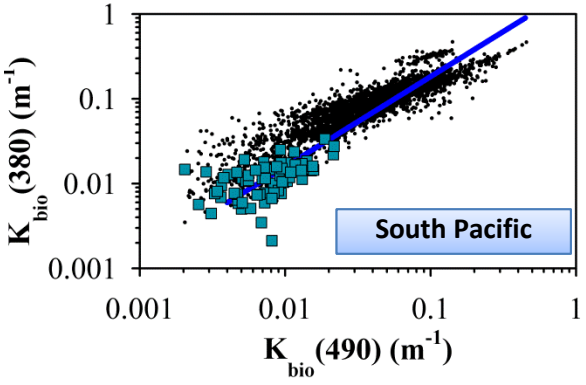
GLOBAL

Morel et al. 2007

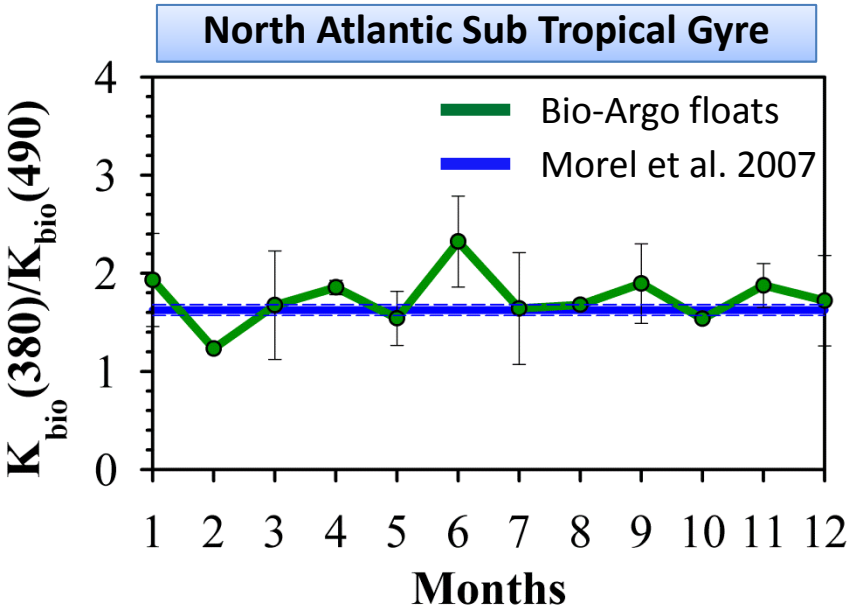
Sub Tropical Gyres

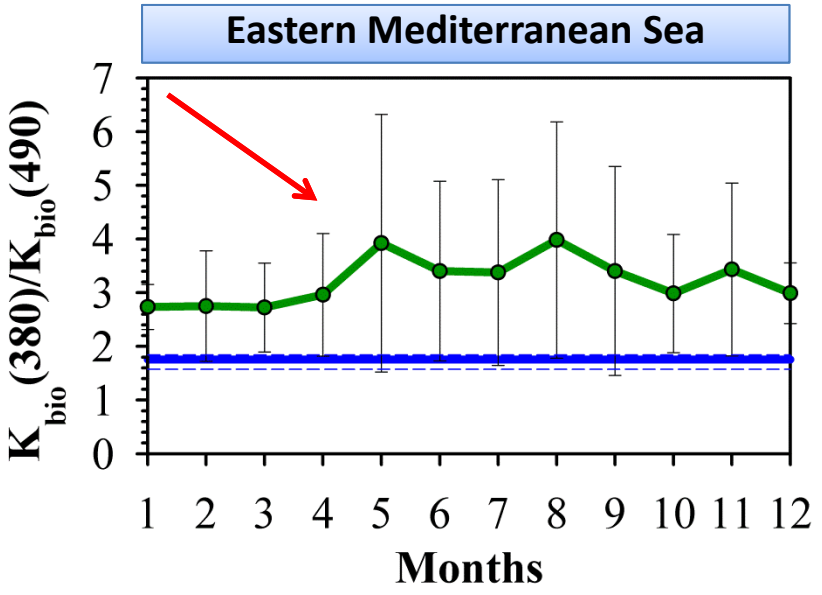


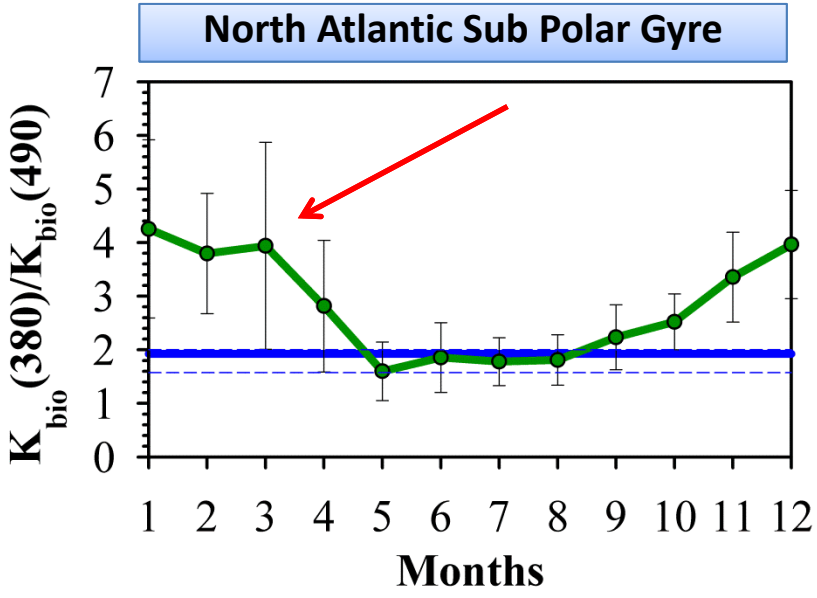


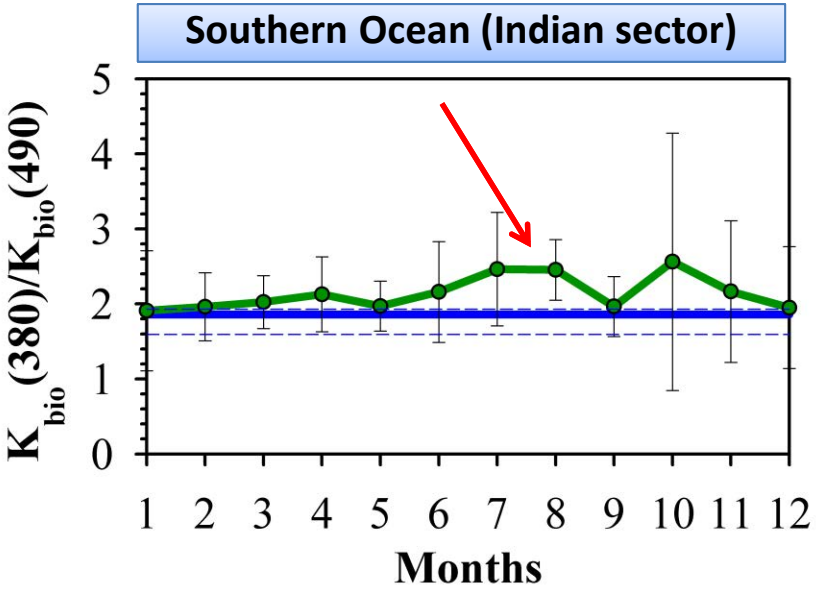


Temporal variability









Long term float deployment and the challenge of « maintaining » calibration over time

- Fluorometers (e.g. Chla and CDOM) => proxies of bio-geochemical or bio-optical quantities (concentration in Chla, CDOM absorption) => calibration required.
- Floats are lost => how "durably accurate" can be an initial calibration (either factory, either in situ) over a 2-3 years lifetime?
- Float network => different calibrations => dataset consistency => big issue if we want to build large database from which (climatic) trends can be extracted over the long term (like the Argo program).

- ***Develop a method to "calibrate" fluorescence (Chla, CDOM) proxies in term of their biogeochemical counterparts over the float life-time***
- ***Evaluate the method through a comparison of multi-float measurements with surface OCR remote sensing of the same quantities.***

General principle of the method

- The diffuse attenuation coefficient is derived from the downwelling irradiance:

  $K_d(\lambda,z) = d[\ln E_d(\lambda,z)]/dz$

- Kd is relatively insensitive to fouling/drift (because a ratio).
- Kd at 490 is **essentially** influenced by Chla concentration, [Chla]

  $K_d(490) = 0.0166 + 0.0825\ [Chla]^{0.6259}$

  (*Morel et al.* 2007)

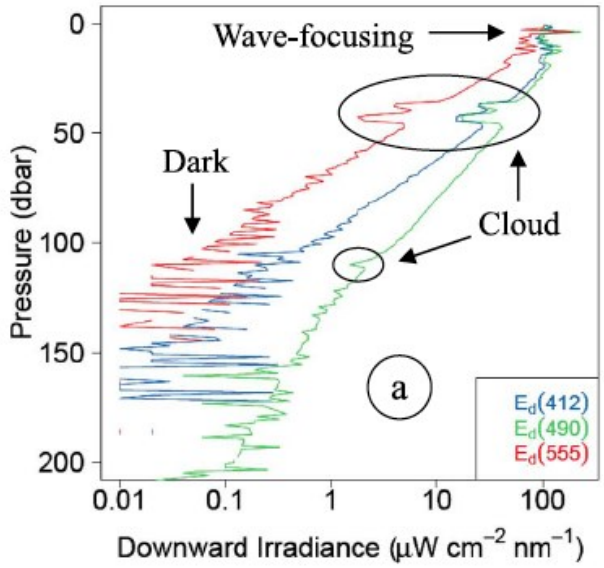
- Kd at 412 is influenced by CDOM absorption, $a_y(412)$ and by [Chla]

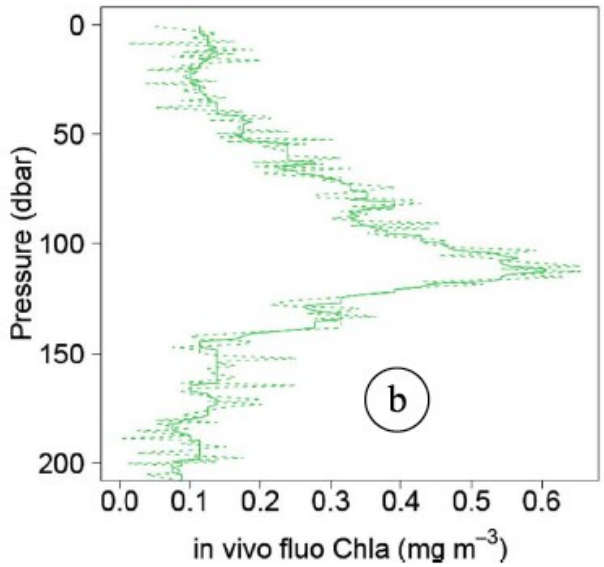
  $K_d(412) = 0.01 + 0.0676[Chla]^{0.686} + 1.3a_y(412)$

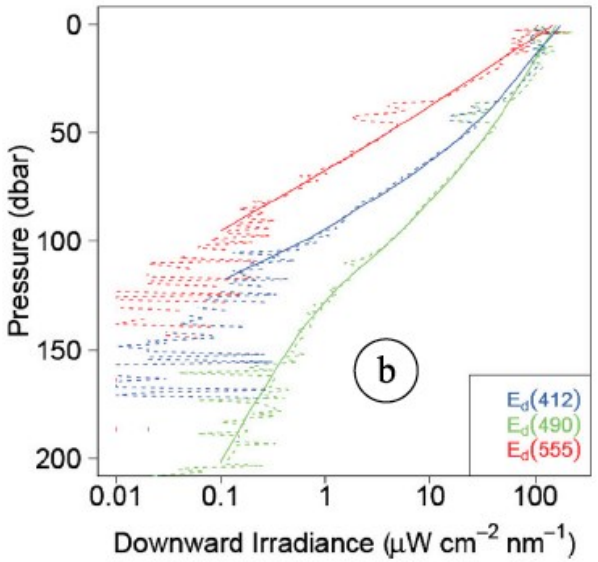
  (*Bricaud et al.* 1998); (*Gordon* 1989)

- Accurate retrieval of [Chla] and $a_y(412)$ based on the combined processing of Ed(λ) and Fluo.

Radiometry + Fluorometry => clean radiometric profile and « calibrated fluorescence »







Chla fluorescence is required for this QC/ correction

Xing et al., JGR, 2011

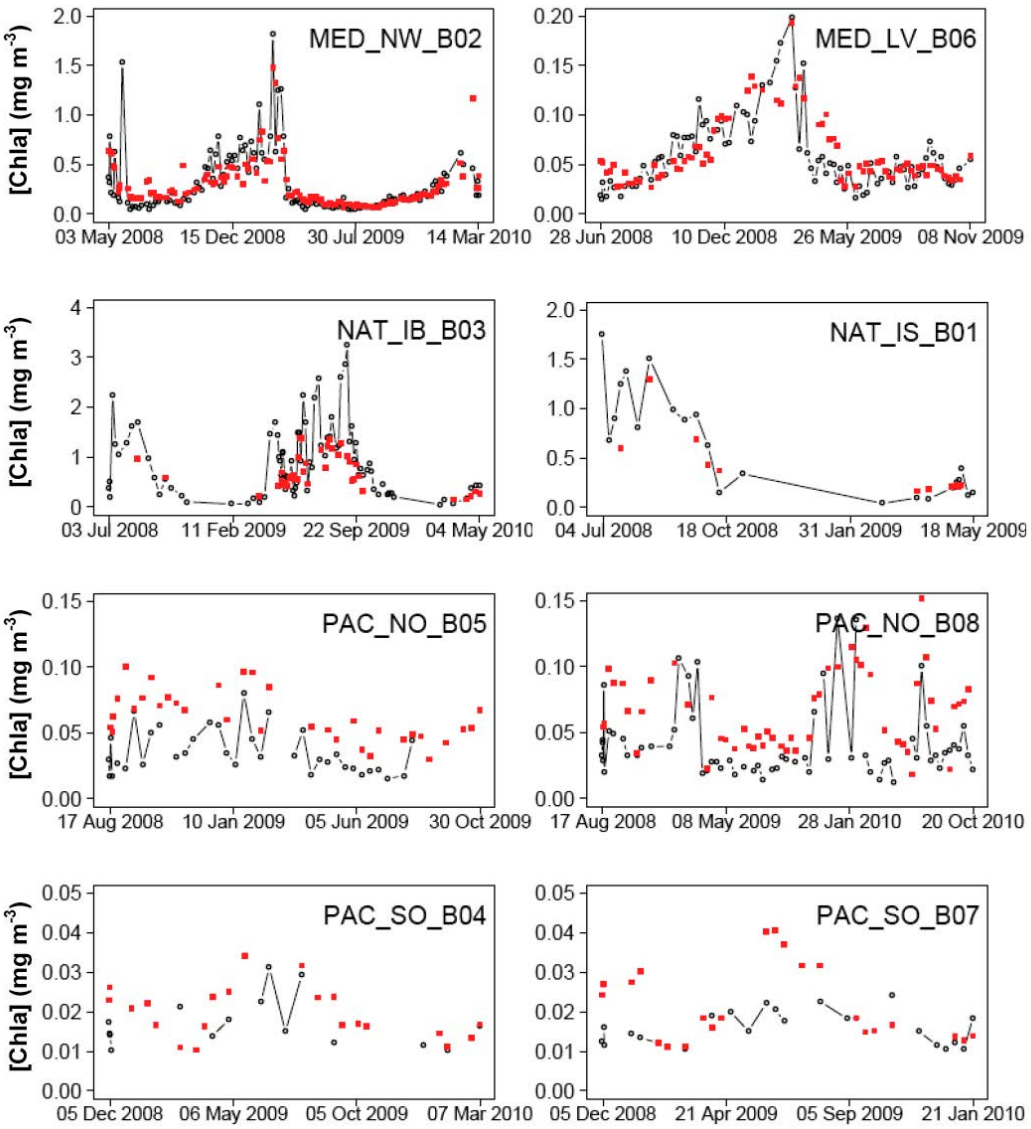
[Chla] retrieval at surface: floats vs MODIS

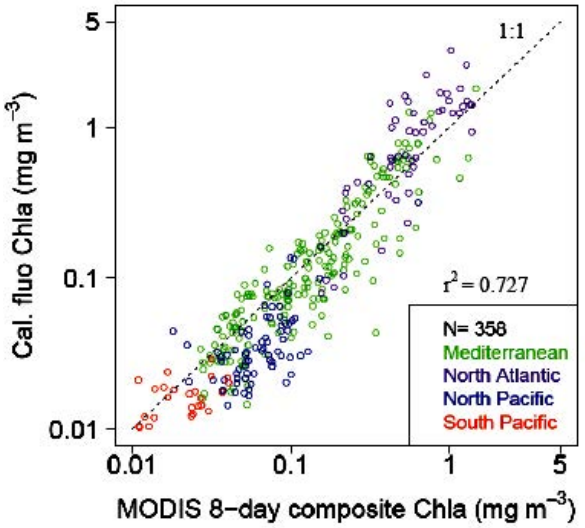
Med Sea

North Atlantic gyre

North Pacific gyre

South Pacific gyre





Float [Chla]

MODIS [Chla]

Xing et al., JGR, 2011

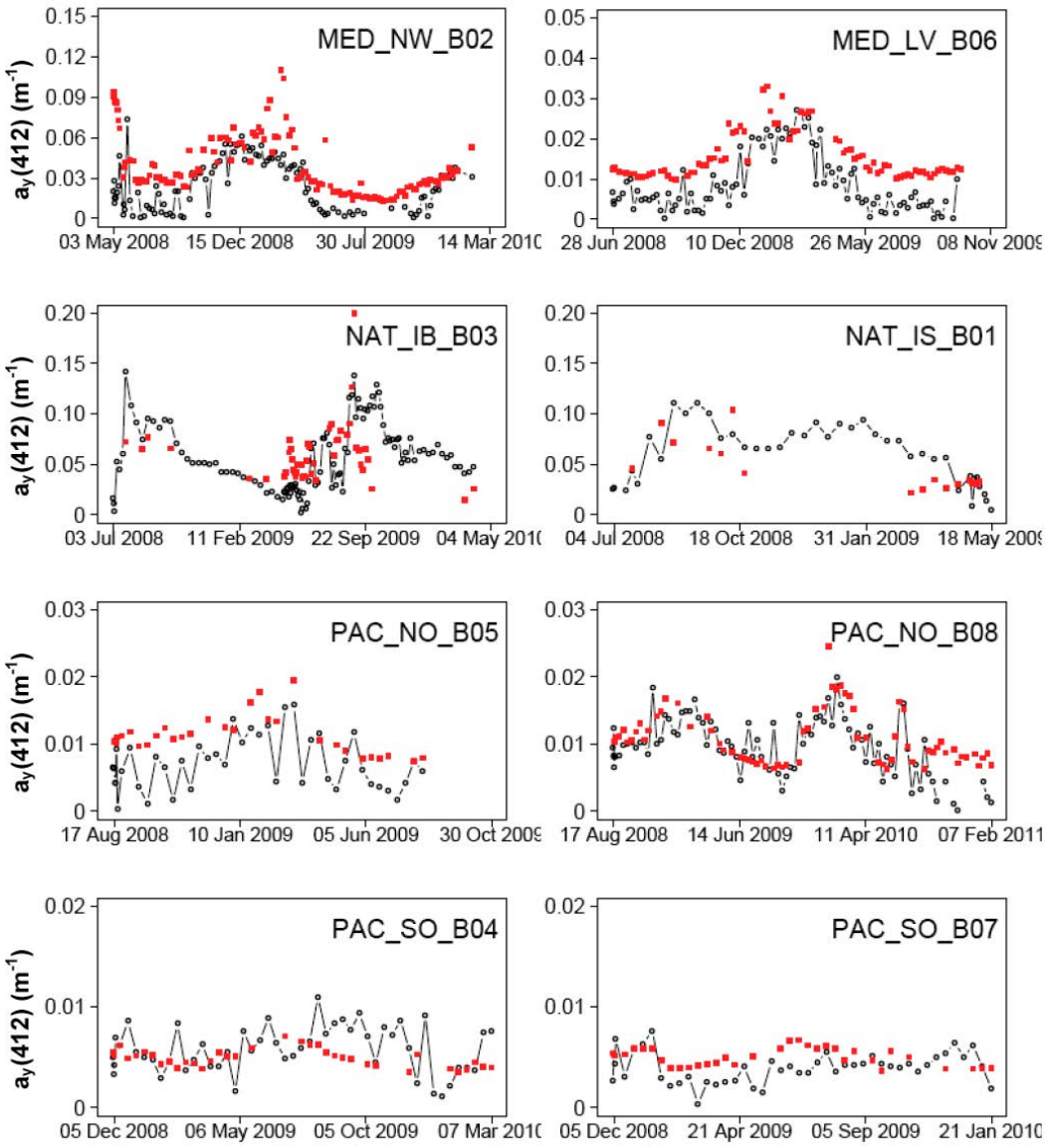
$a_y(412)$ retrieval at surface: floats vs MODIS

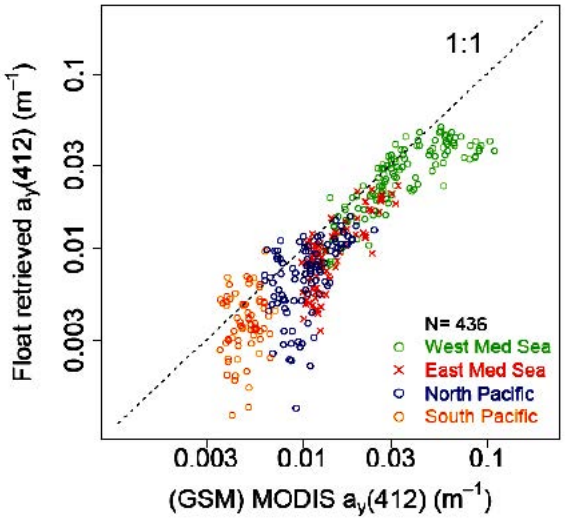
Med Sea

North Atlantic gyre

North Pacific gyre

South Pacific gyre





Float $a_y(412)$

MODIS $a_y(412)$ via GSM $a_{dg}(443)$

Xing et al., JGR, 2012

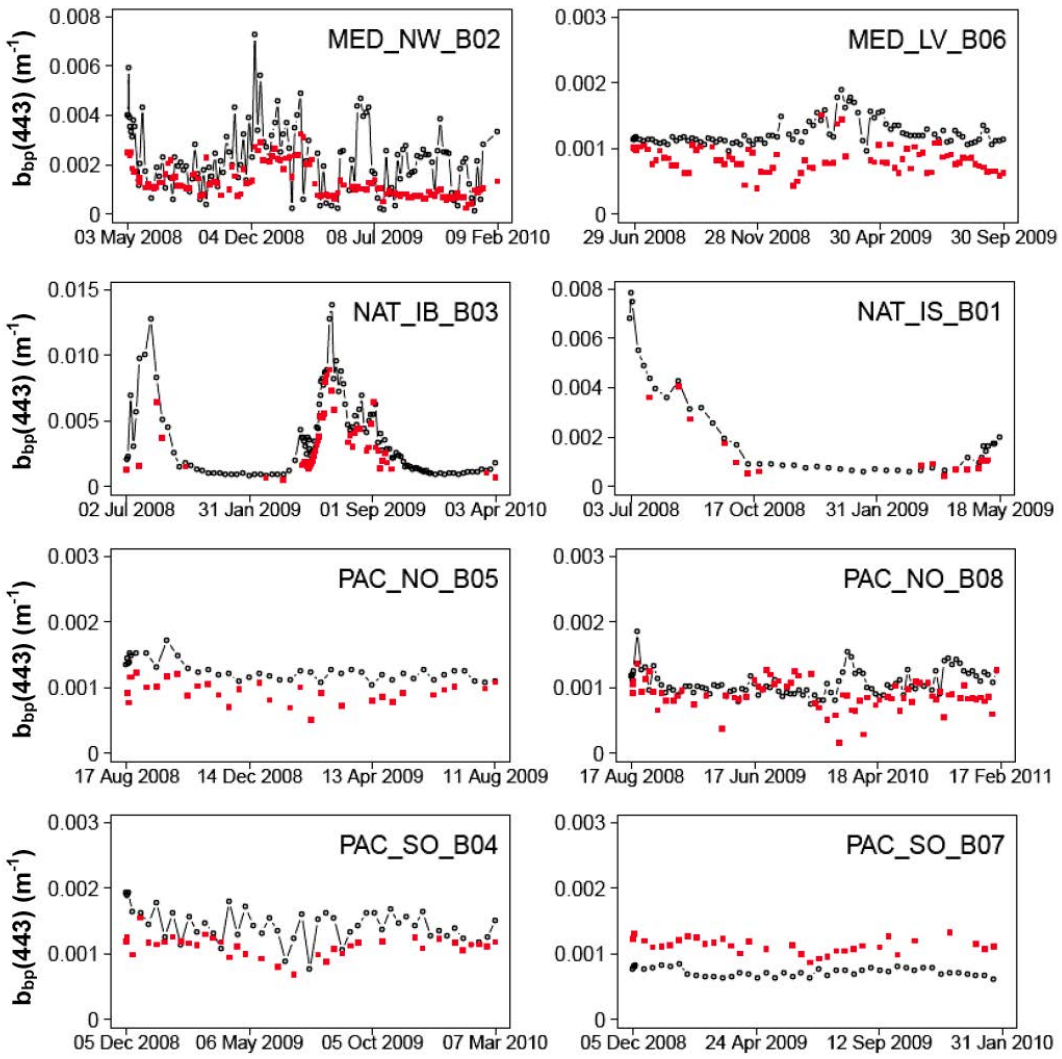
b_{bp} (POC proxy): floats vs MODIS

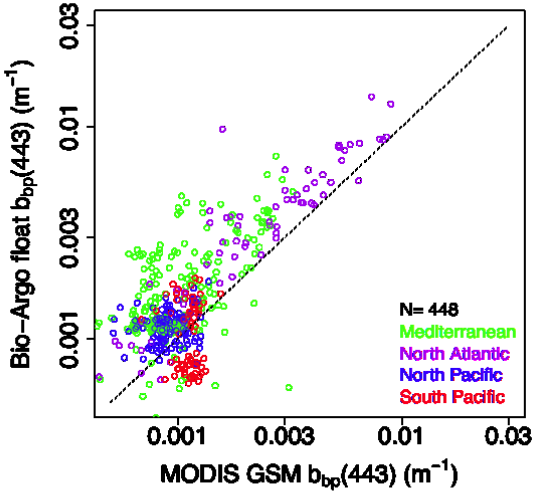
Med Sea

North Atlantic gyre

North Pacific gyre

South Pacific gyre



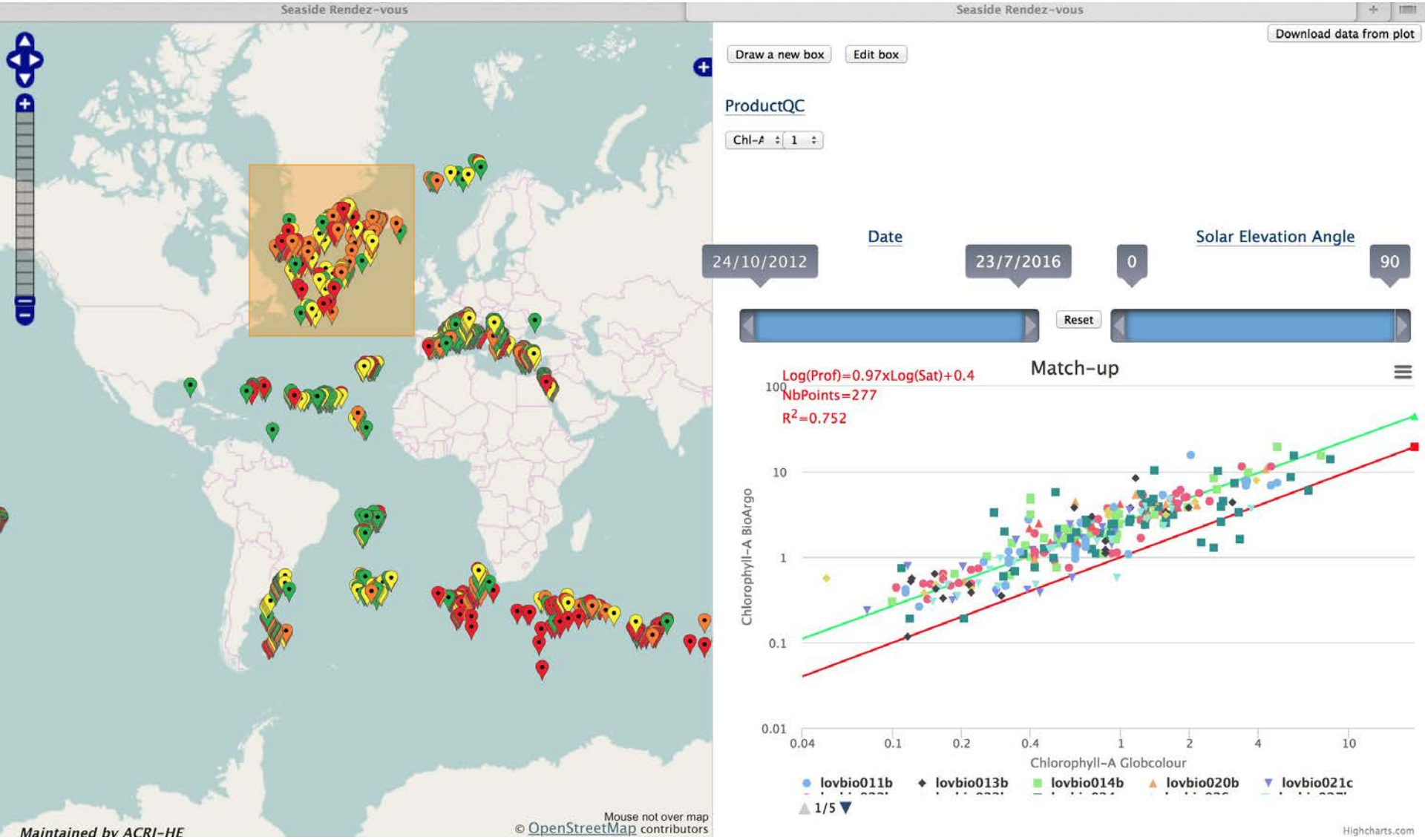


Float $b_{bp}(532)$

MODIS $b_{bp}(443)$

Matchup analysis: Bio-Argo vs Globcolour product

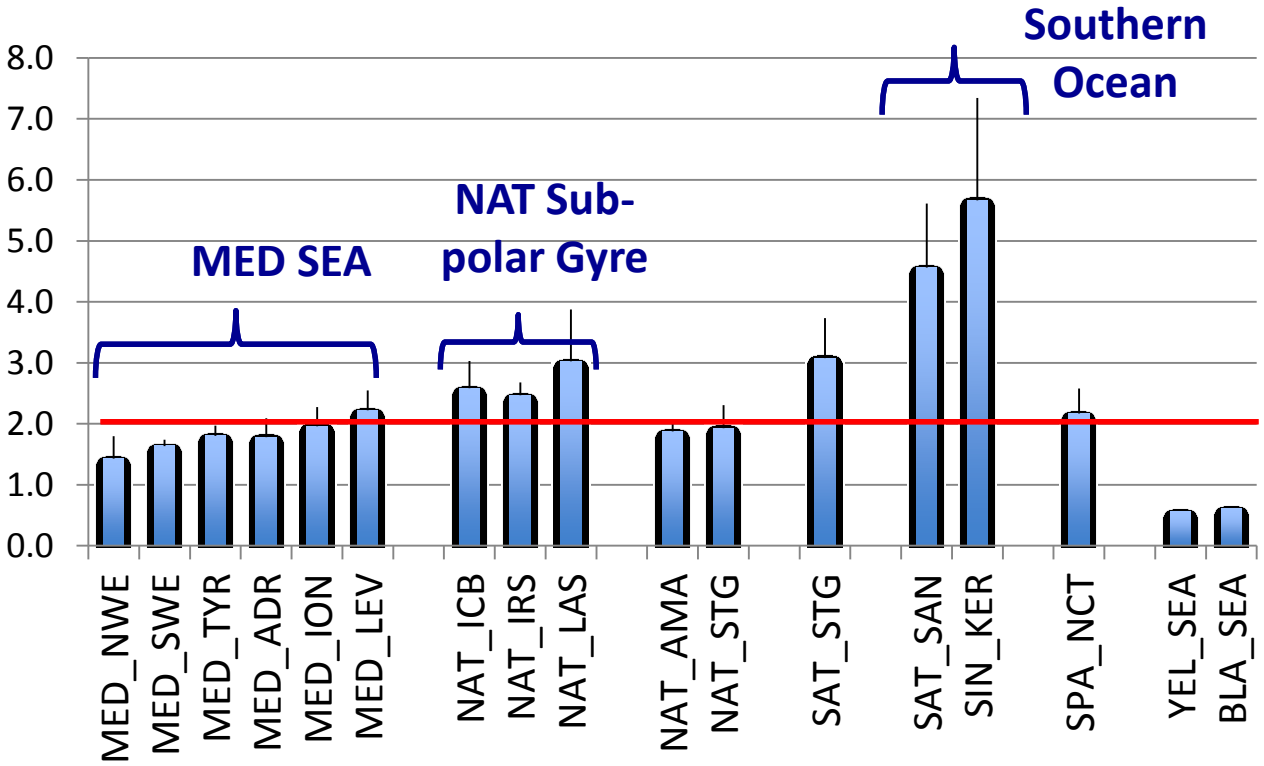
http://seasiderendezvous.fr/matchup.php



Satellite vs Bio-Argo matchups analysis

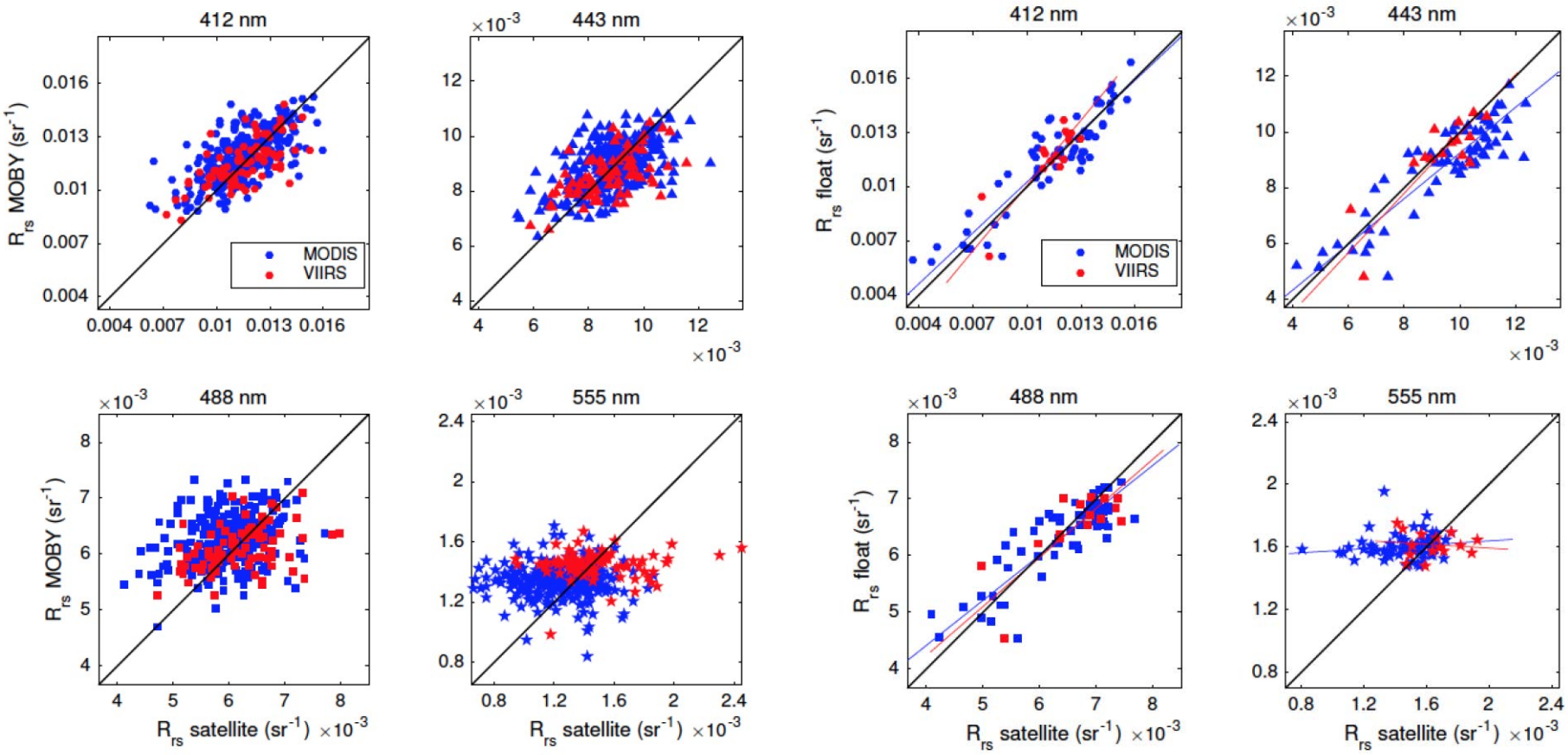
A potential bias in the fluorometer calibration??

Over 9000 fluorescence and radiometric profiles



- **Ratio** between **factory calibrated Chl** and **radiometry derived Chl** (Xing et al., 2011*), which is totally independent to the fluorometer Chl
- An **average factor of 2 appears**

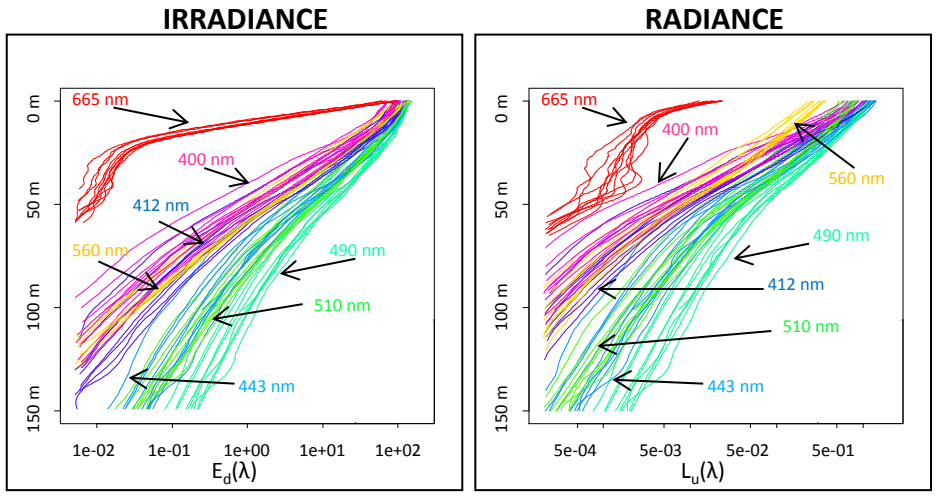
First OCR cal-VAL studies using dedicated floats

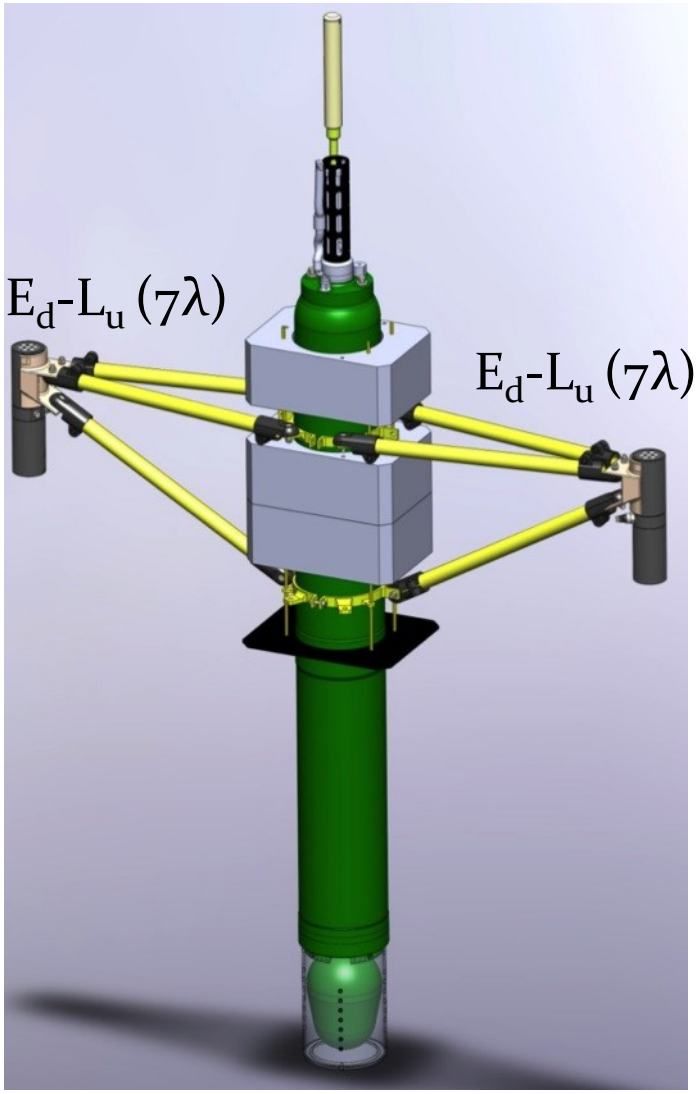


Gerbi et al., JAOT, in revision

Development of the PROVAL: a float dedicated to cal-val applications

- New CTS5 Profiler
- 2 E_d-L_u sensors
  - E_d : 380, 412, 443, 490, 510, 560, 665 nm + PAR
  - Lu : 380, 412, 443, 490, 510, 560, 665 nm
- Tilt and compass
- Chla, CDOM and backscattering





Conclusions

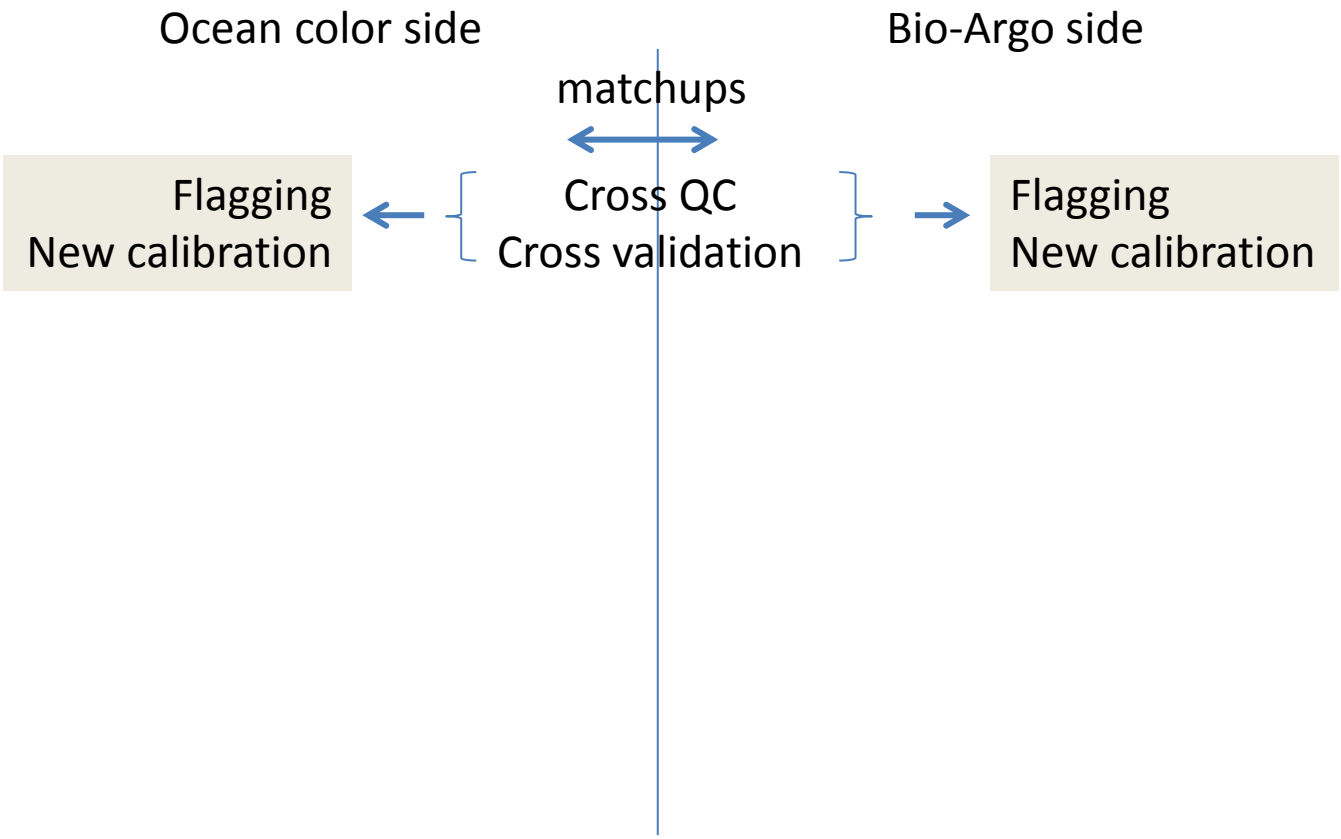
Opportunities for joint use of Bio-Argo and Ocean Color

Ocean color side

In situ Bio-Argo side

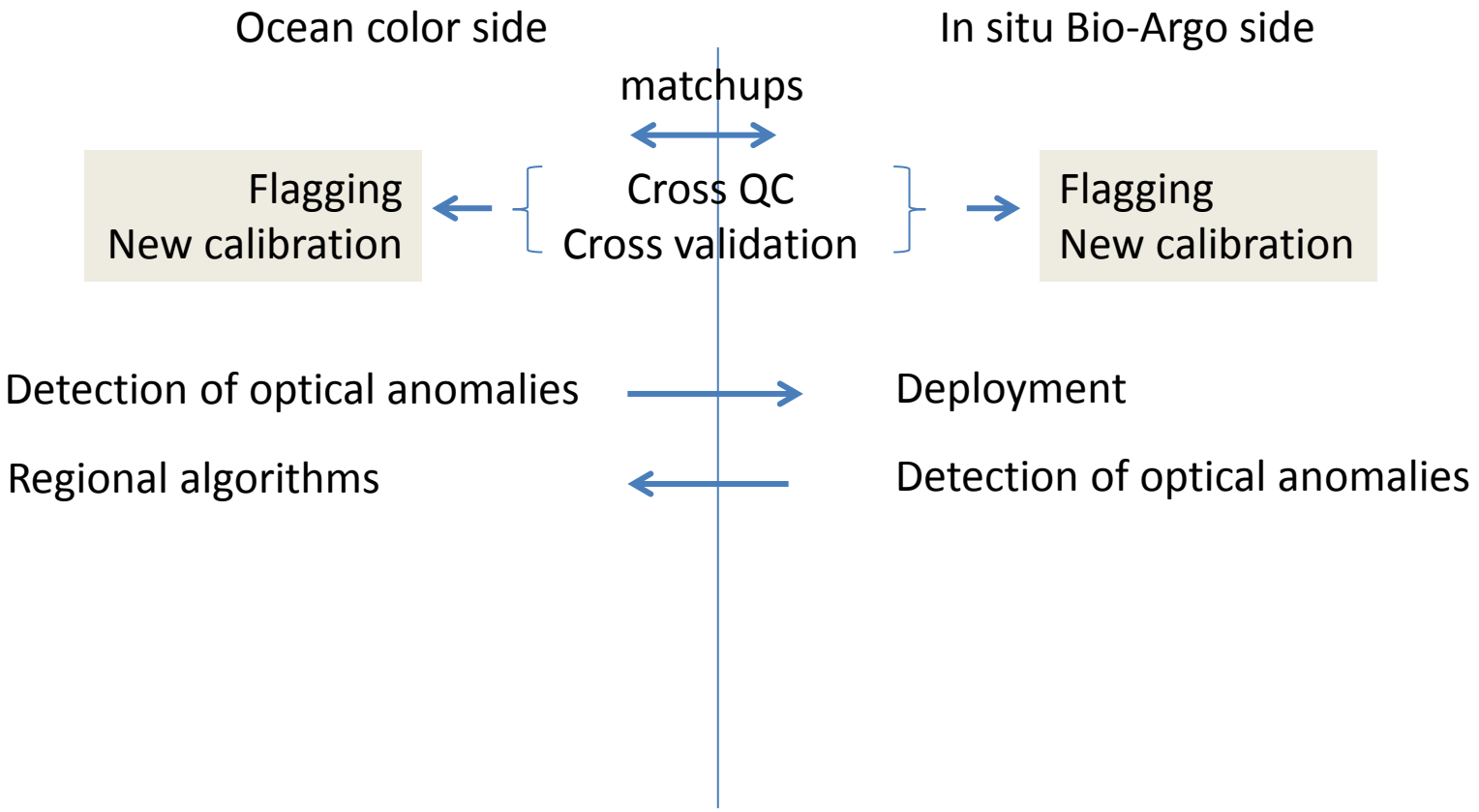
Conclusions

Opportunities for joint use of Bio-Argo and Ocean Color



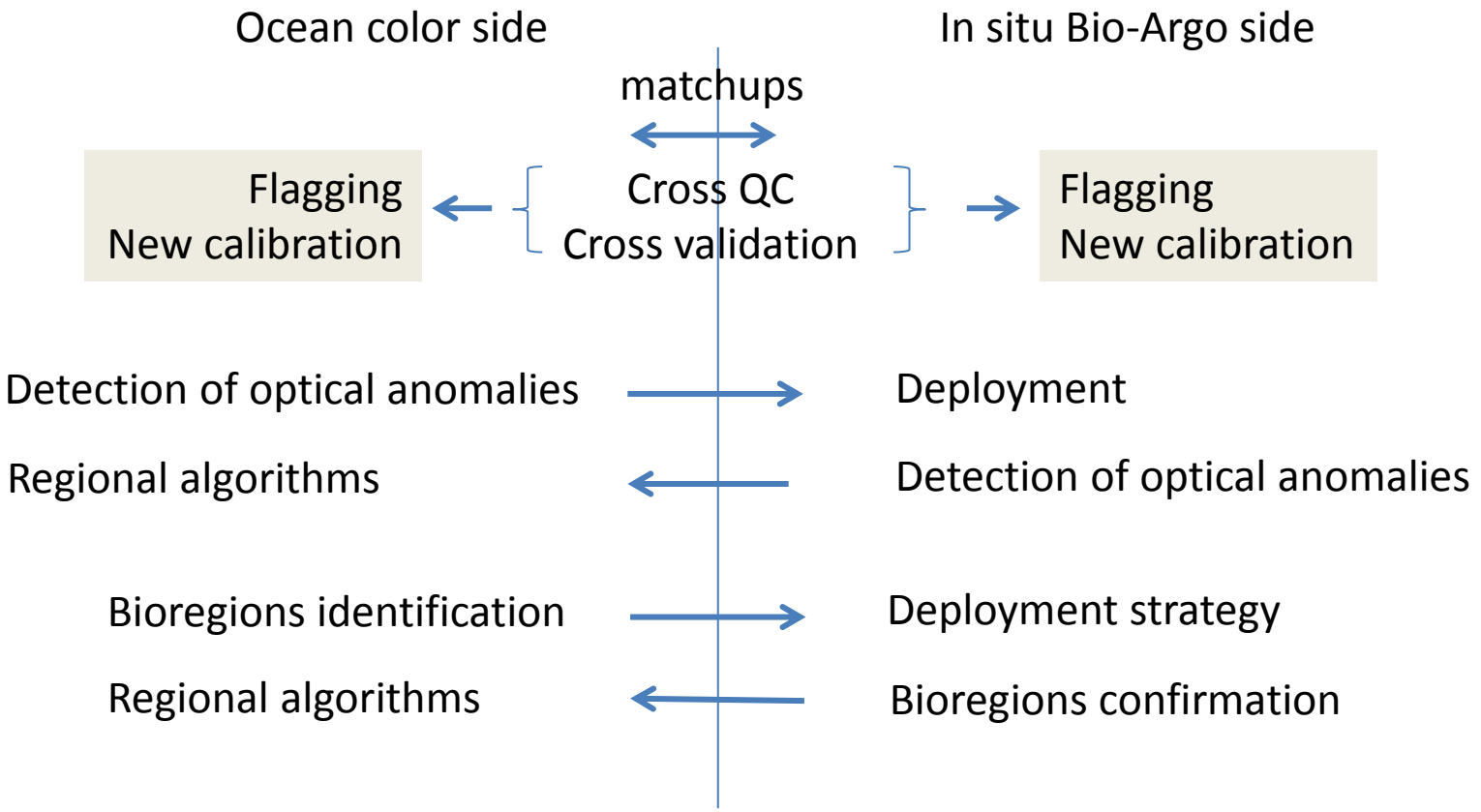
Conclusions

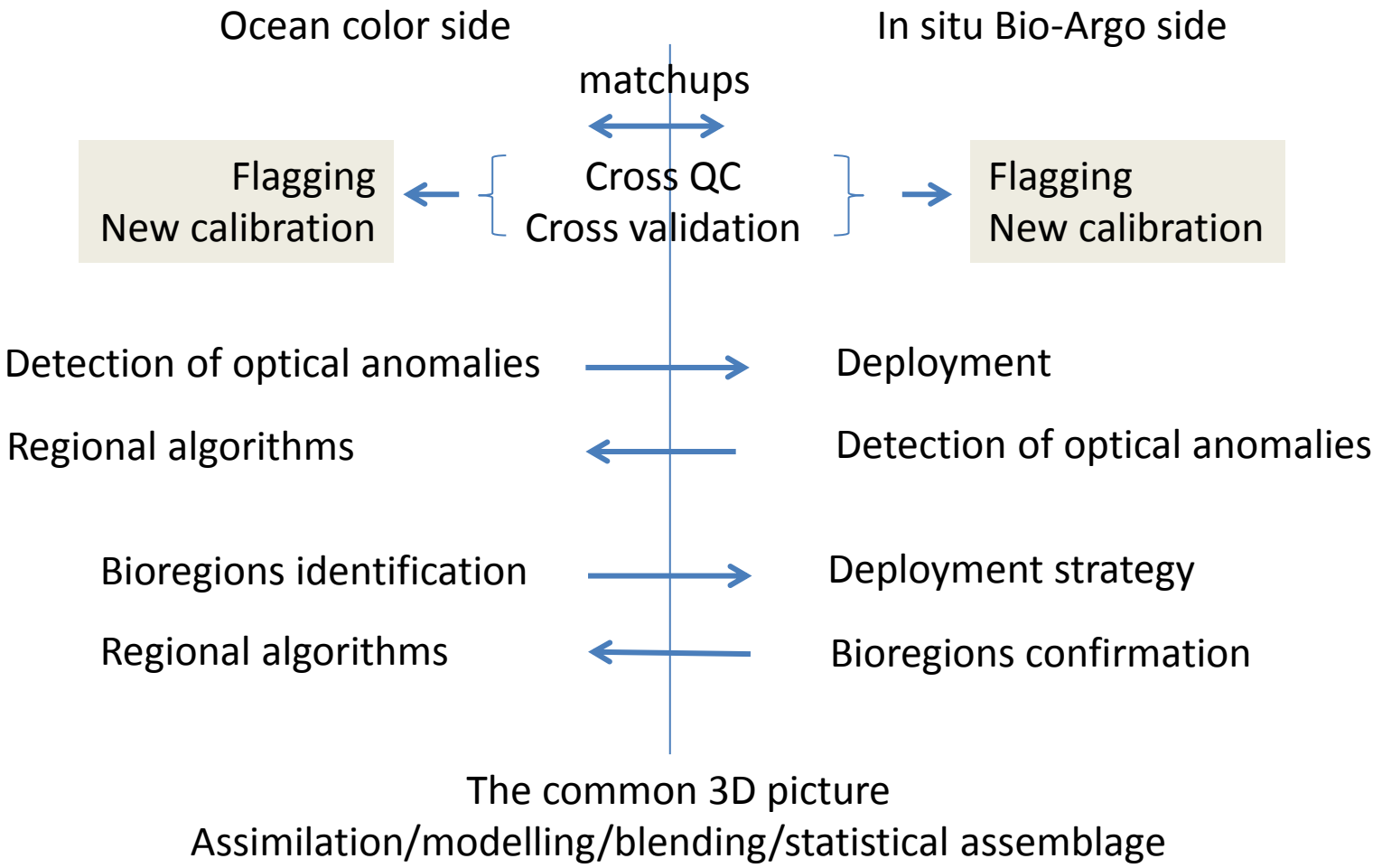
Opportunities for joint use of Bio-Argo and Ocean Color



Conclusions

Opportunities for joint use of Bio-Argo and Ocean Color



Conclusions

Opportunities for joint use of Bio-Argo and Ocean Color